

The Nodal Metal in Cuprates: A New State of Matter?

Mike Norman

Materials Science Division
Argonne National Laboratory

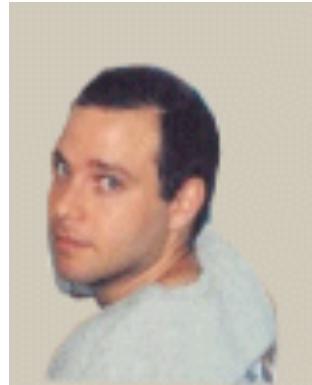
Kanigel *et al.*, Nature Physics 2, 447 (2006)



Trieste, Aug. 21, 2006

The Team

Amit KANIGEL (**UIC/Argonne**)



Mike NORMAN (**Argonne**)



Mohit RANDERIA (**Ohio State**)



Utpal CHATTERJEE (**UIC**)



Seigo SOUMA (**UIC/Sendai**)



Adam KAMINSKI (**Ames**)

Helen FRETWELL (**Ames**)

Stephan ROSENKRANZ (**Argonne**)

Ming SHI (**UIC/PSI**)

Takafumi SATO (**Sendai**)

Takashi TAKAHASHI (**Sendai**)

Z. Z. LI (**Orsay**)

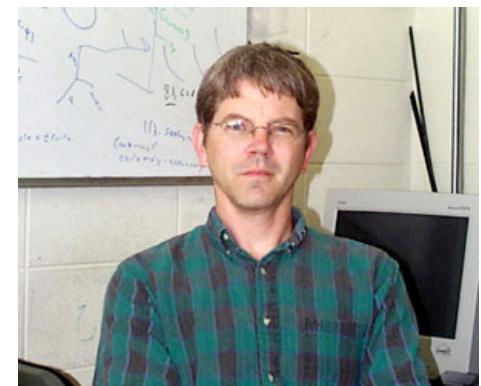
Helene RAFFY (**Orsay**)

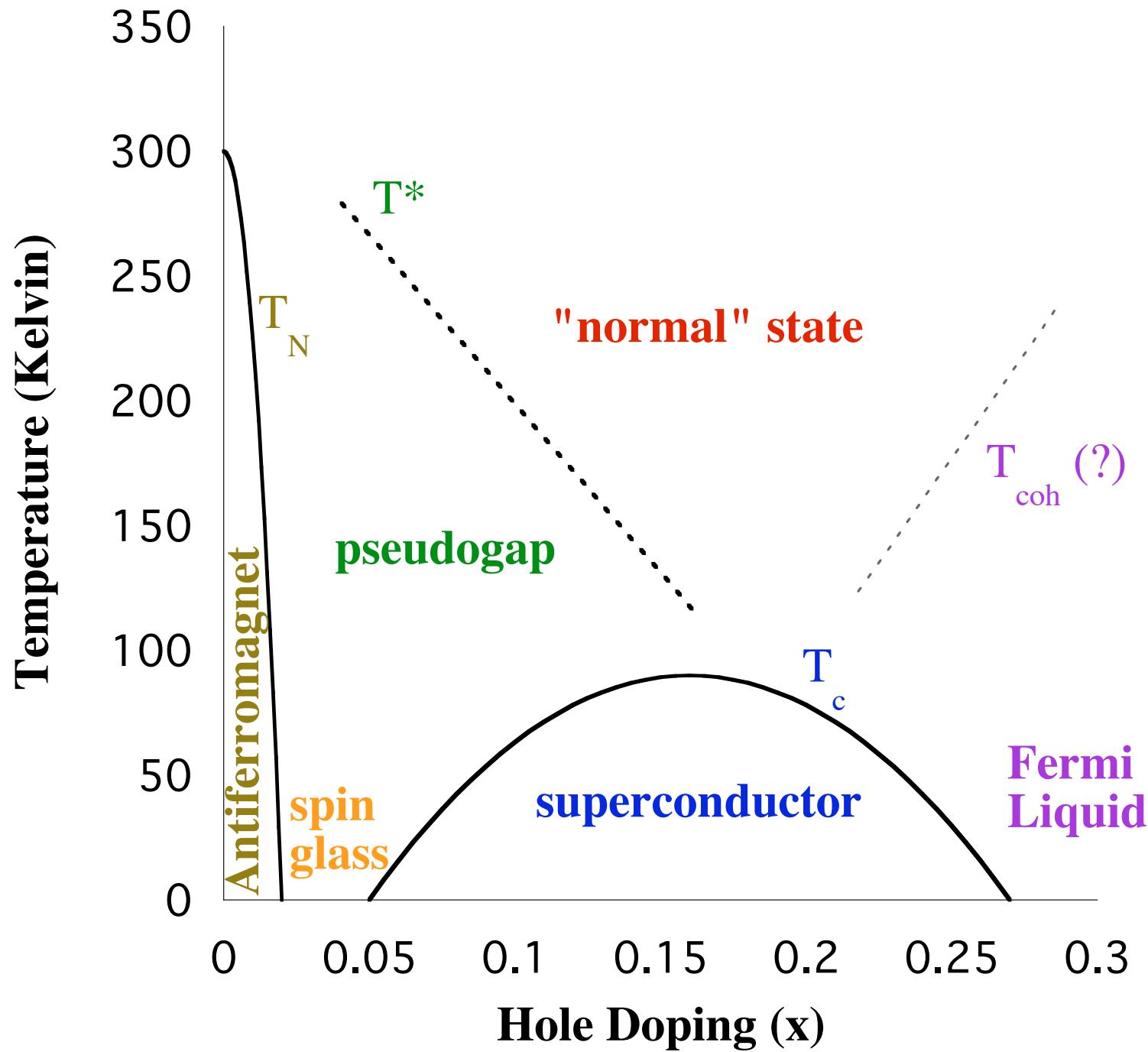
Kazuo KADOWAKI (**Tsukuba**)

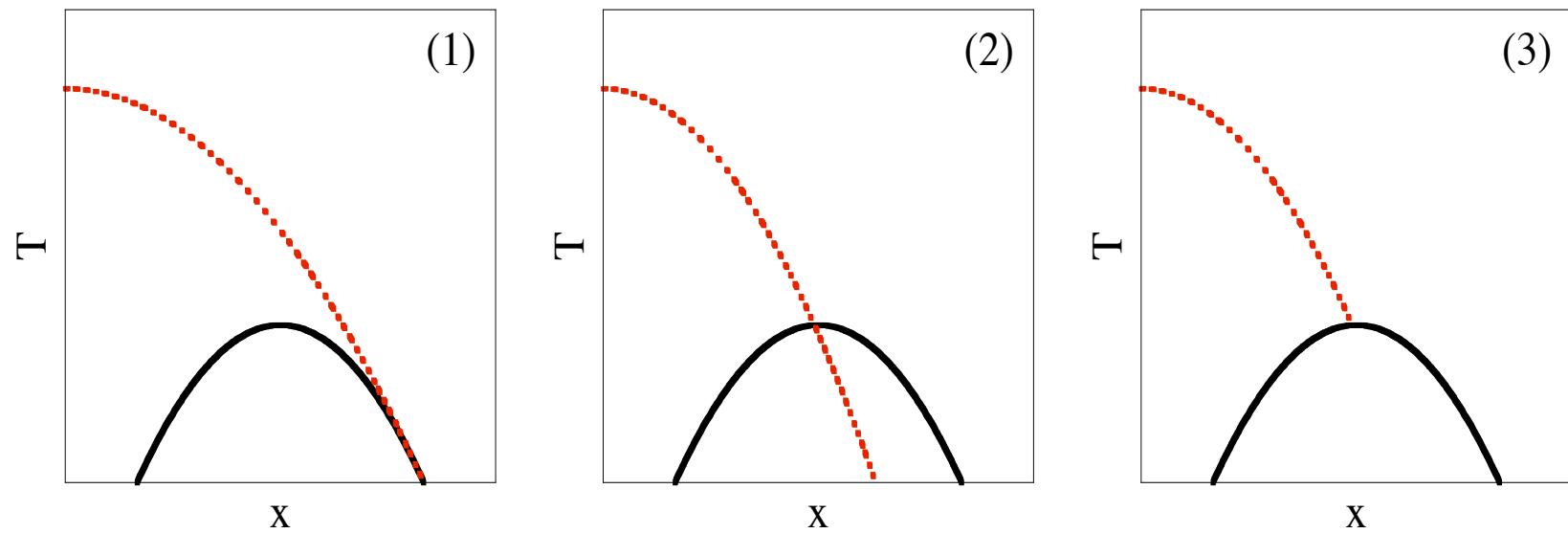
David HINKS (**Argonne**)

Lufti OZYUZER (**Argonne**)

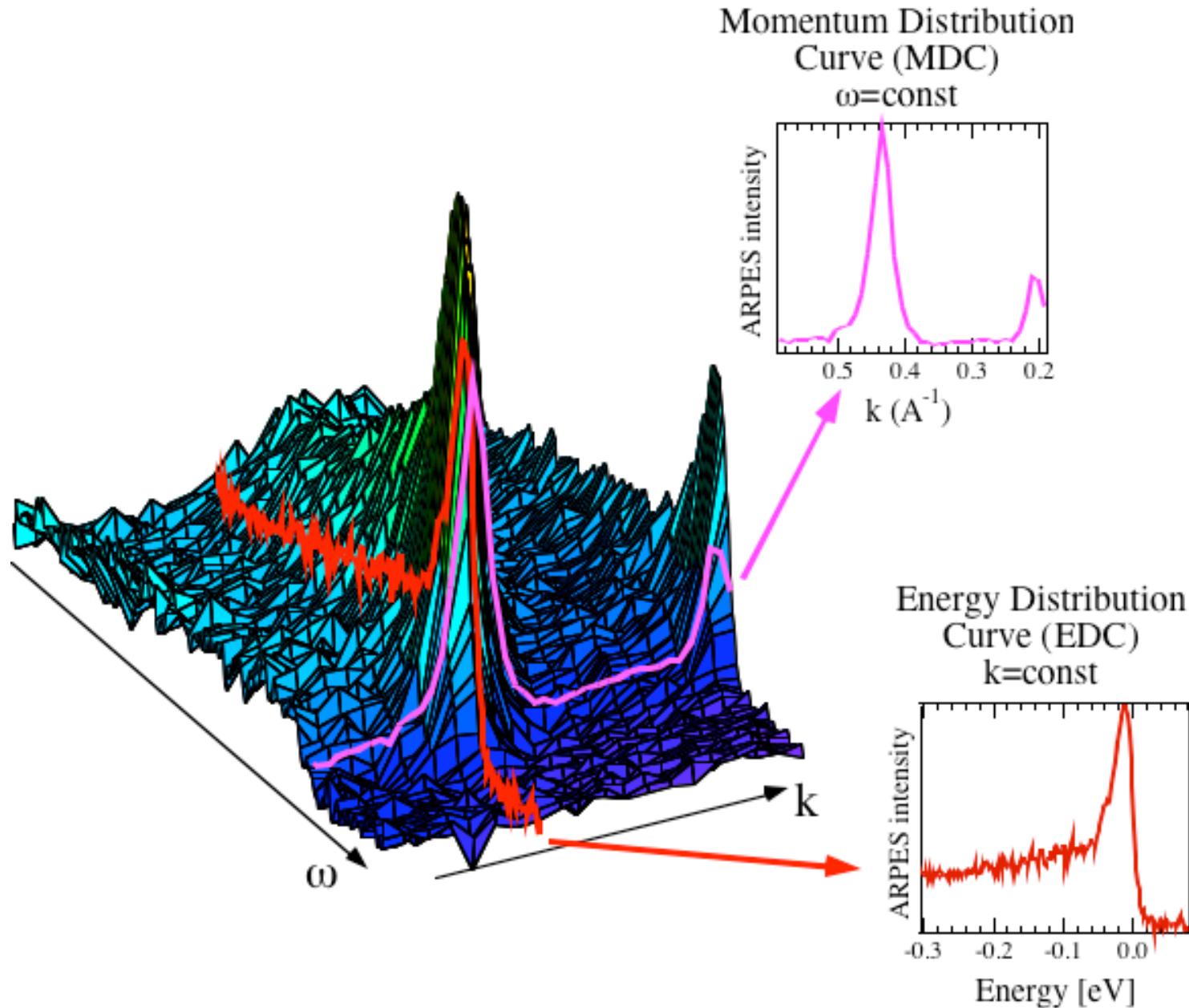
Juan Carlos CAMPUZANO (**UIC/Argonne**)







Angle Resolved Photoemission Spectroscopy (ARPES)

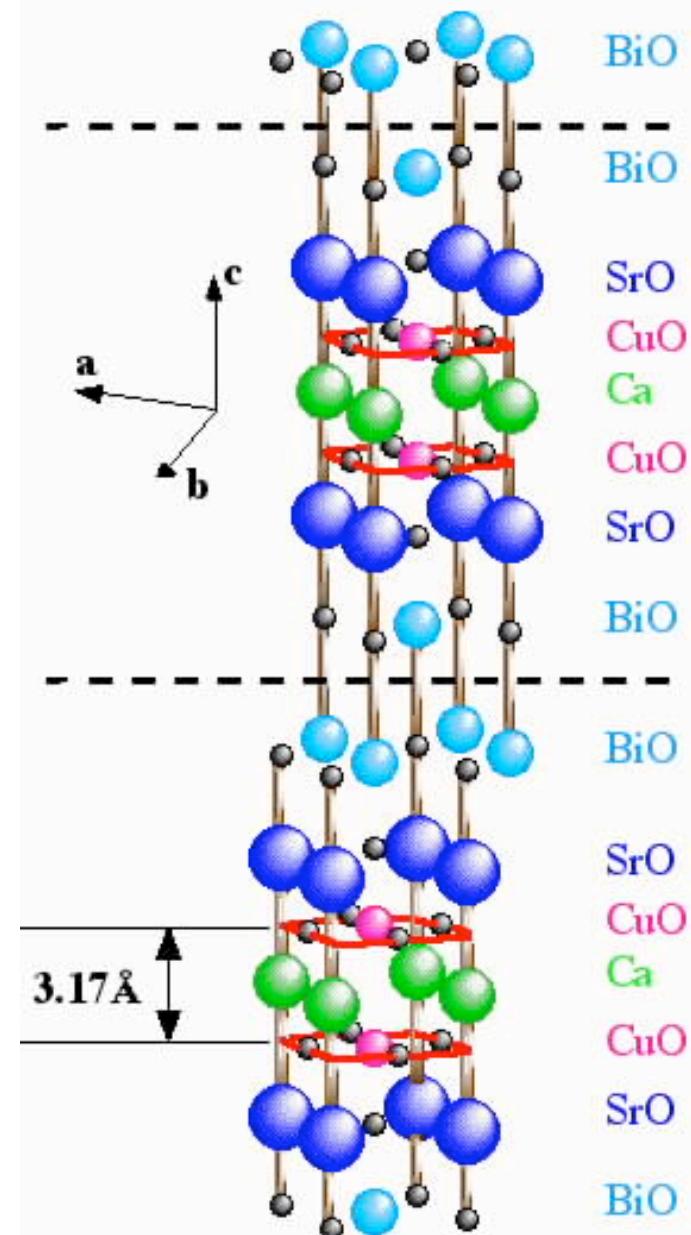


Assuming the “sudden approximation”, ARPES in 2D systems measures the single particle spectral function

$$I(\mathbf{k},\omega) = c \langle A(\mathbf{k},\omega)f(\omega) \rangle + \text{background} \quad \text{where}$$

1. A is the single particle spectral function
2. f is the Fermi-Dirac function
3. c is the square of the dipole matrix element (plus intensity normalization)
4. $\langle \rangle$ is the convolution with the energy resolution gaussian and sum over the momentum window
5. background is secondaries plus other contributions

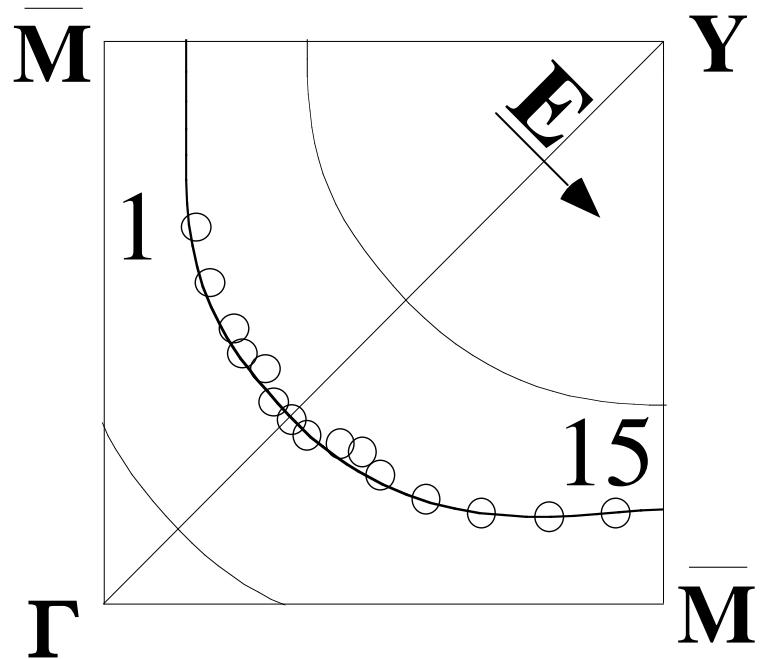
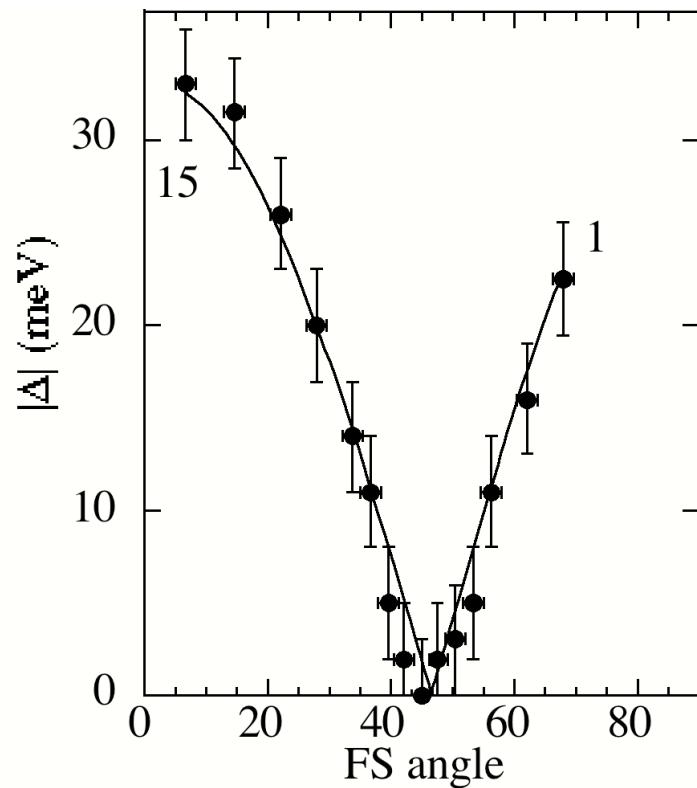
Bi2212



Extraction of the Superconducting Energy Gap

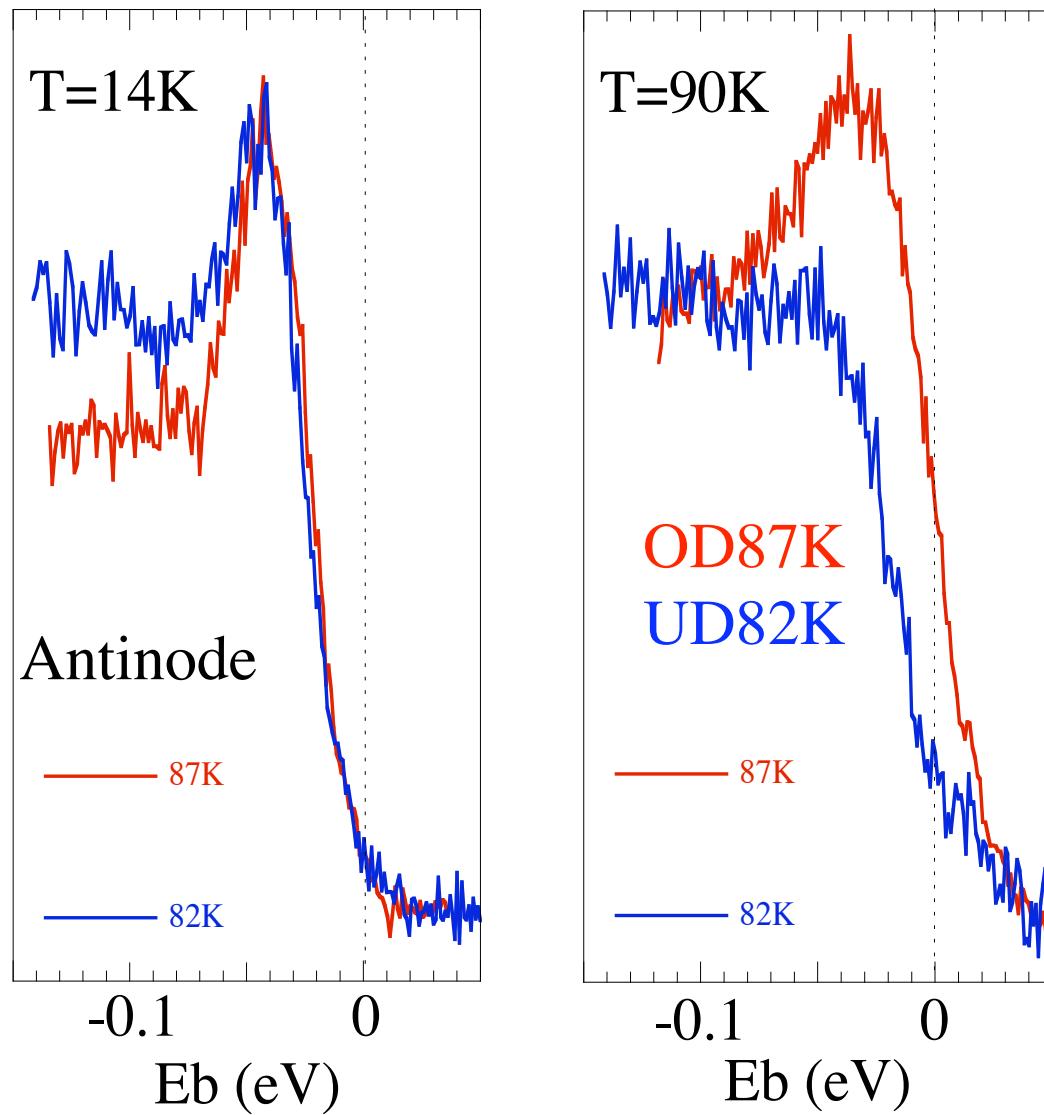
Ding *et al.*, PRL 74, 2784 (1995) & PRB 54, 9678 (1996)

$\Delta_k \rightarrow \cos(k_x) - \cos(k_y) \rightarrow$ Implies near-neighbor pairs

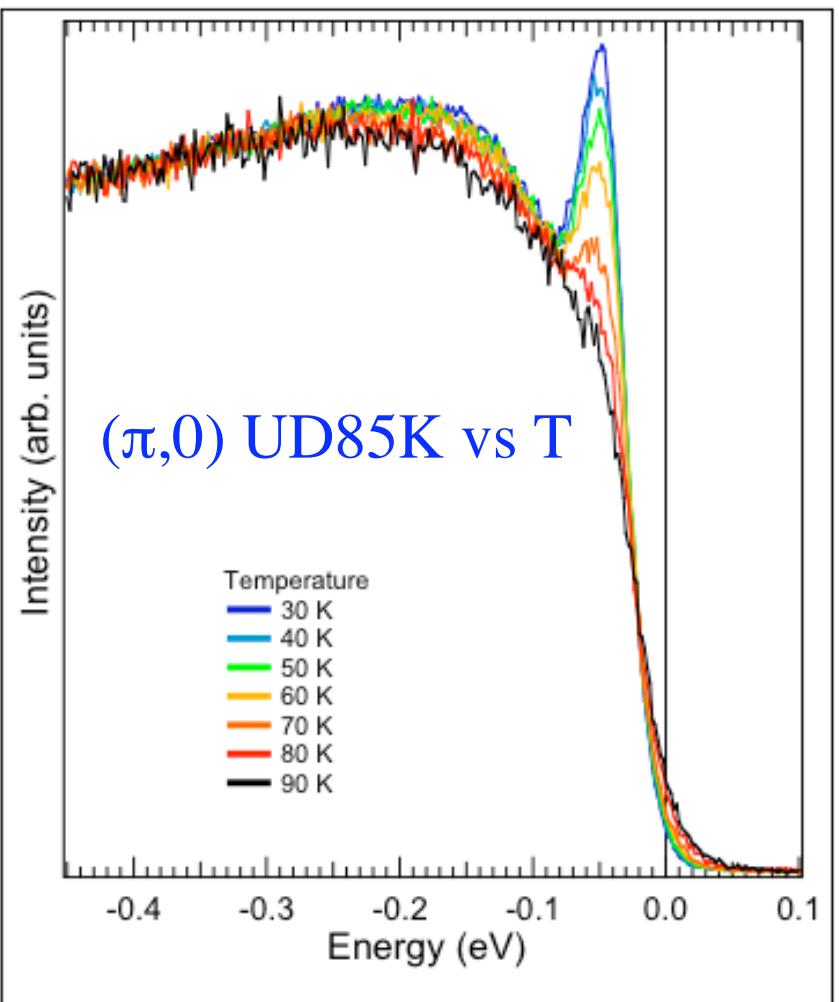
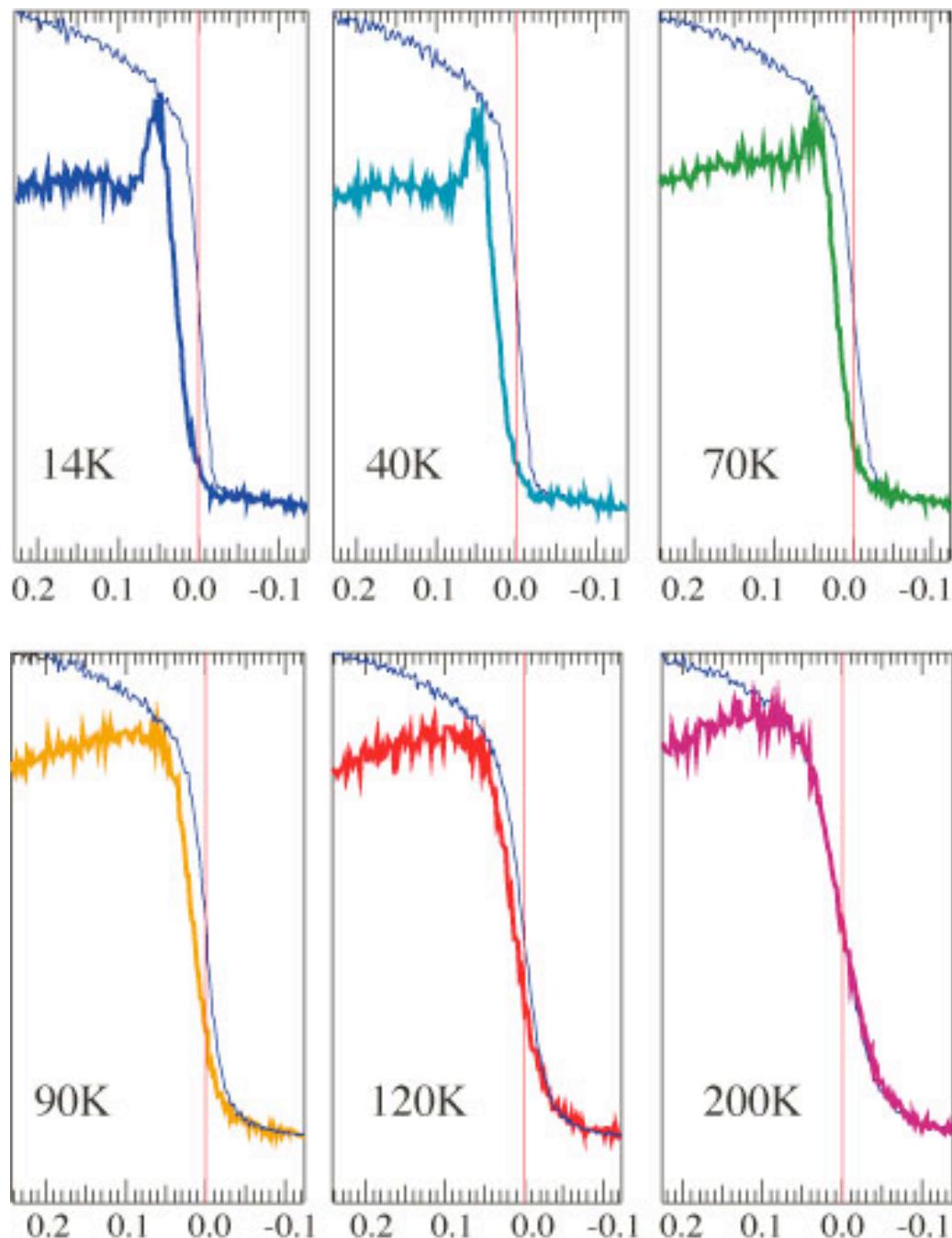


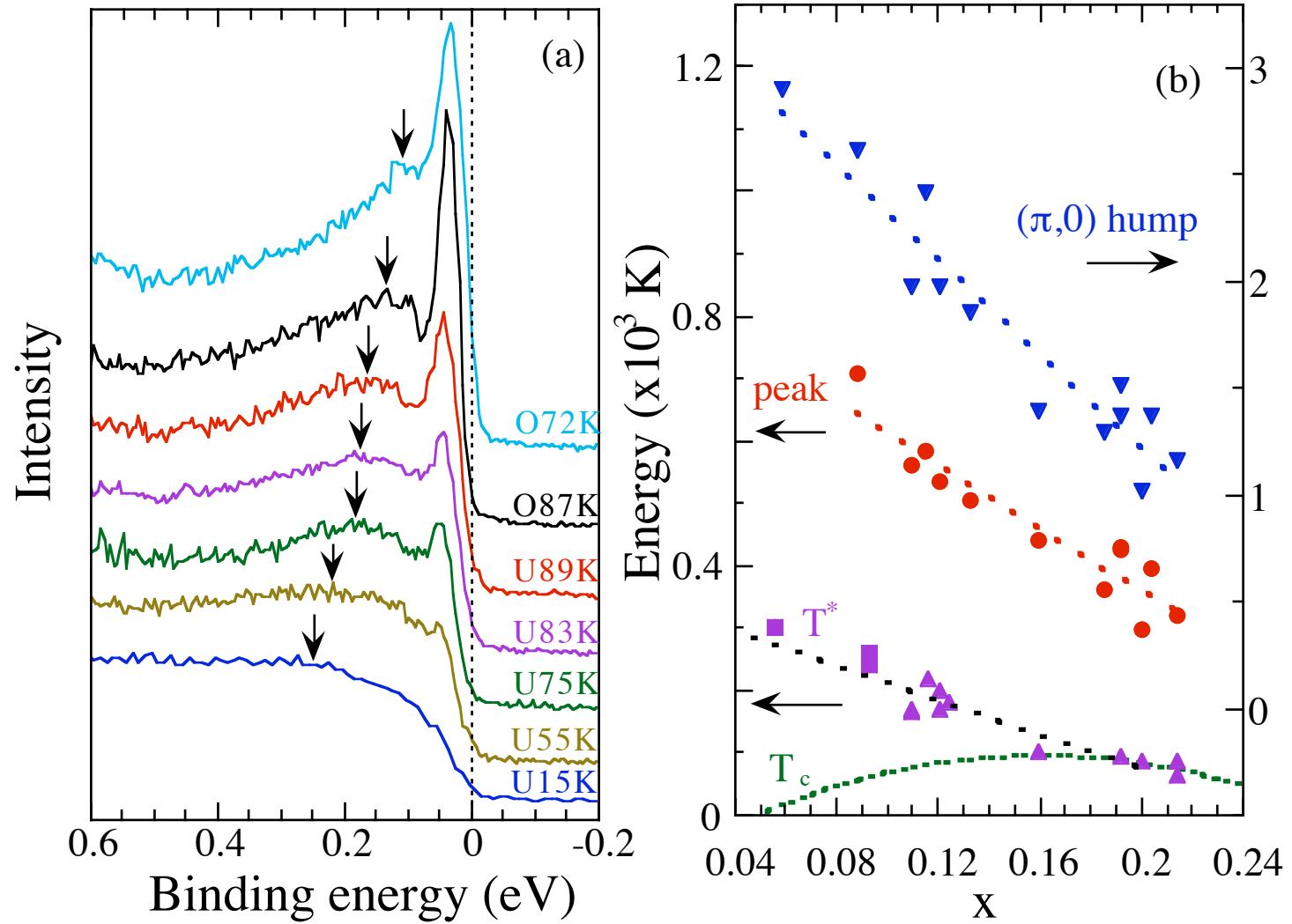
Bi2212
overdoped, $T_c=87\text{K}$
(OD87K)

ARPES - Ding *et al.*, Nature 382, 51 (1996)
pseudogap - spectral gap but no coherent peak



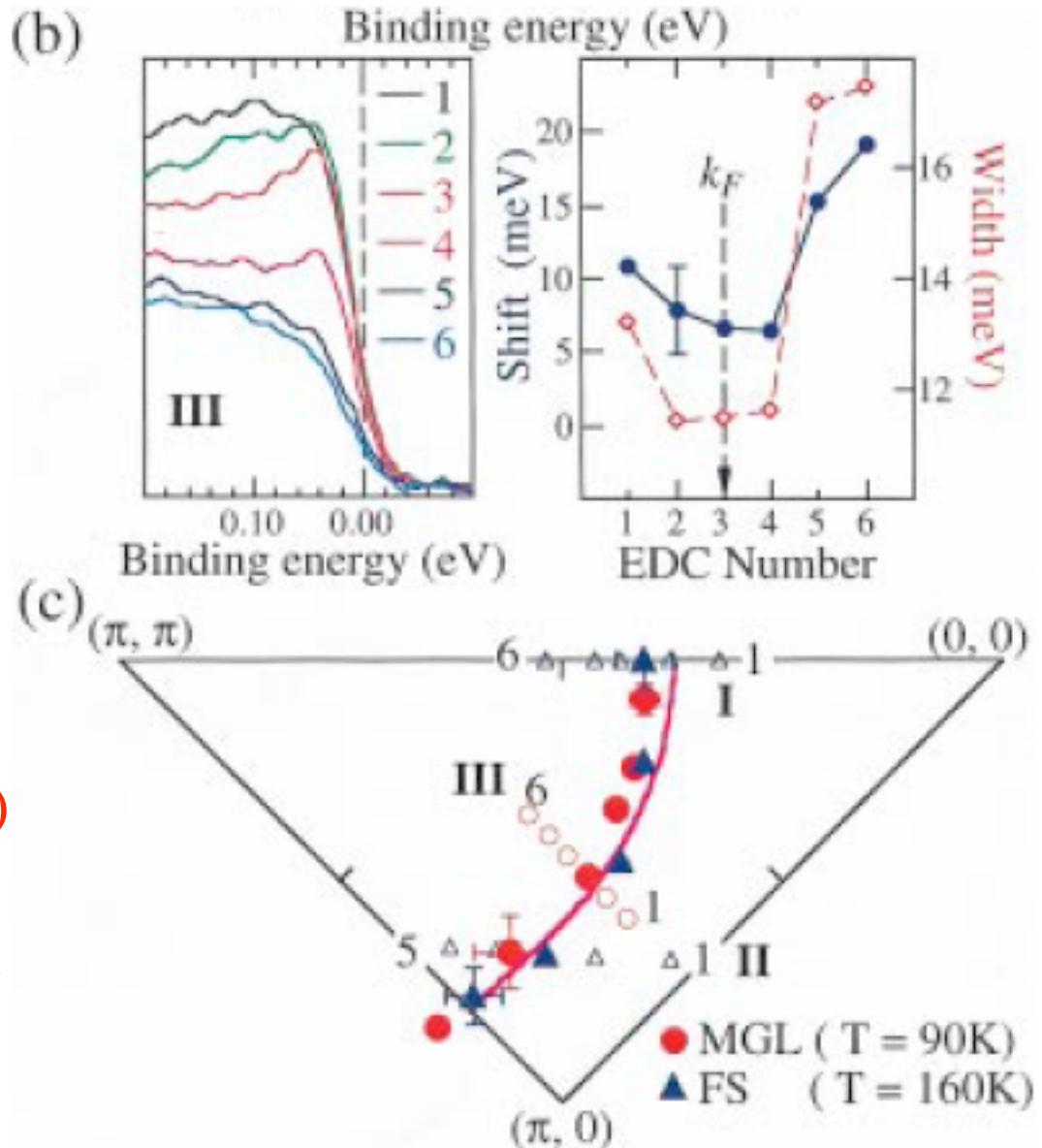
<-- Antinode UD83K vs T





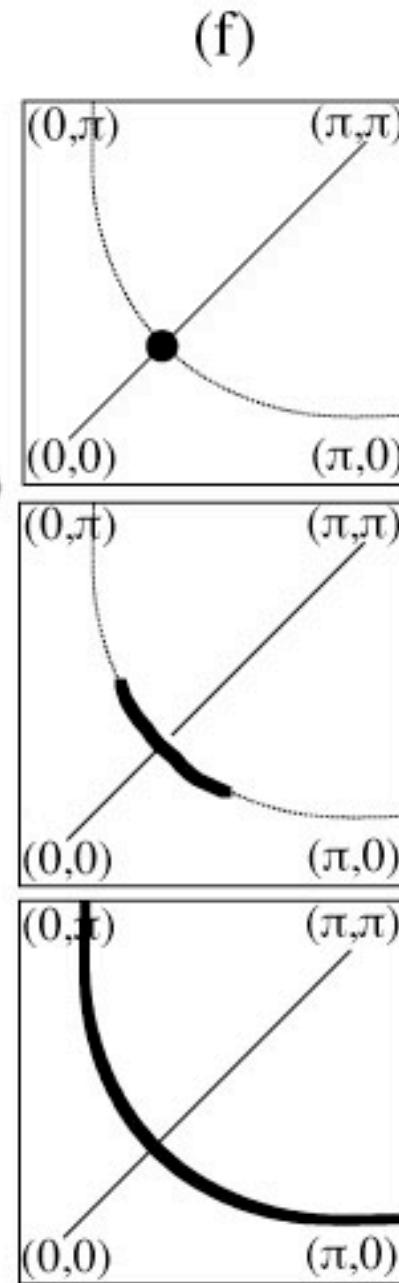
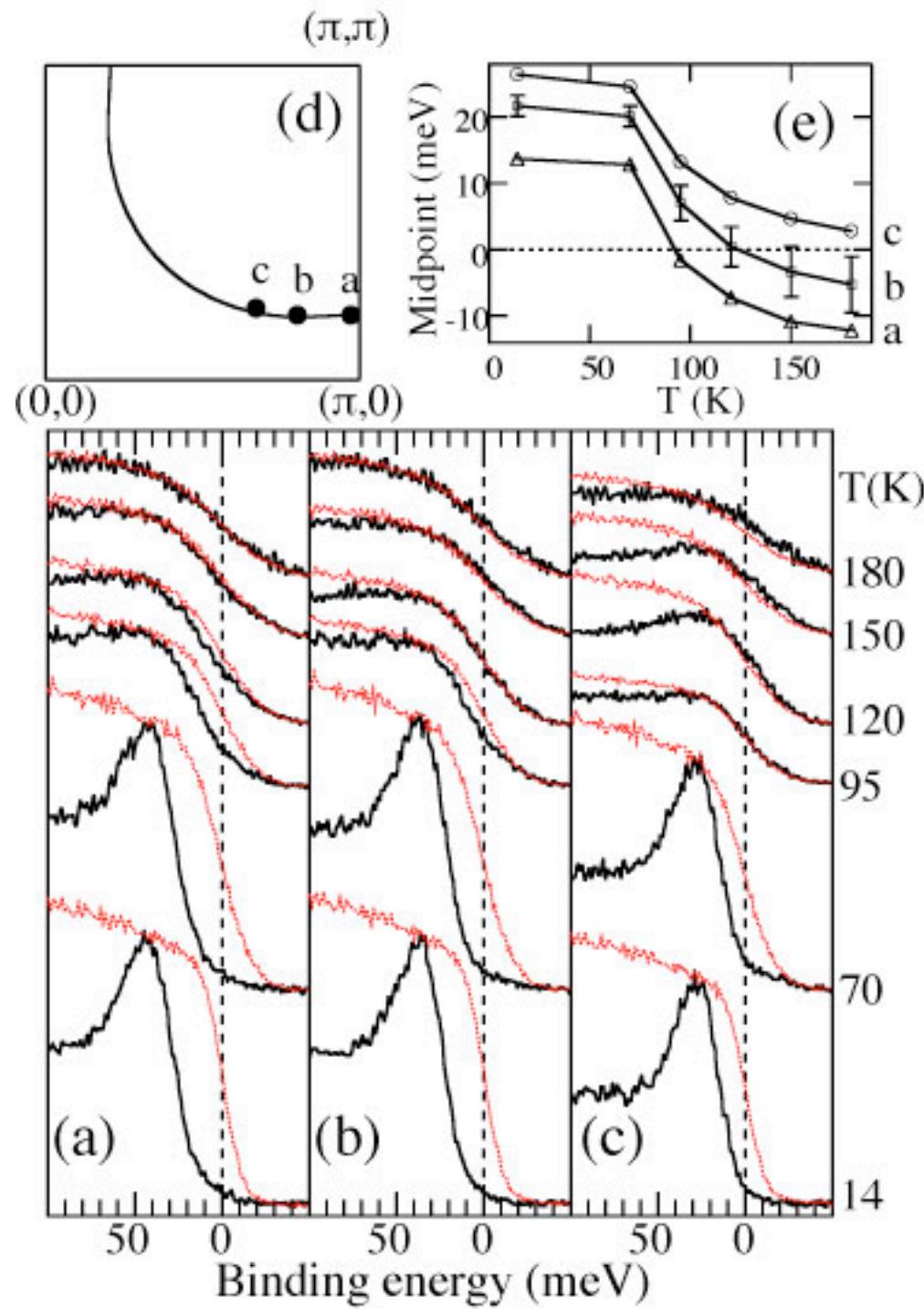
Left - $(\pi,0)$ spectra versus doping (arrow marks the hump)
Right - Energy scales (peak, hump, T^* , T_c) versus doping

“Fermi surface” in the presence of an energy gap
Ding *et al.*, PRL 78, 2628 (1997)

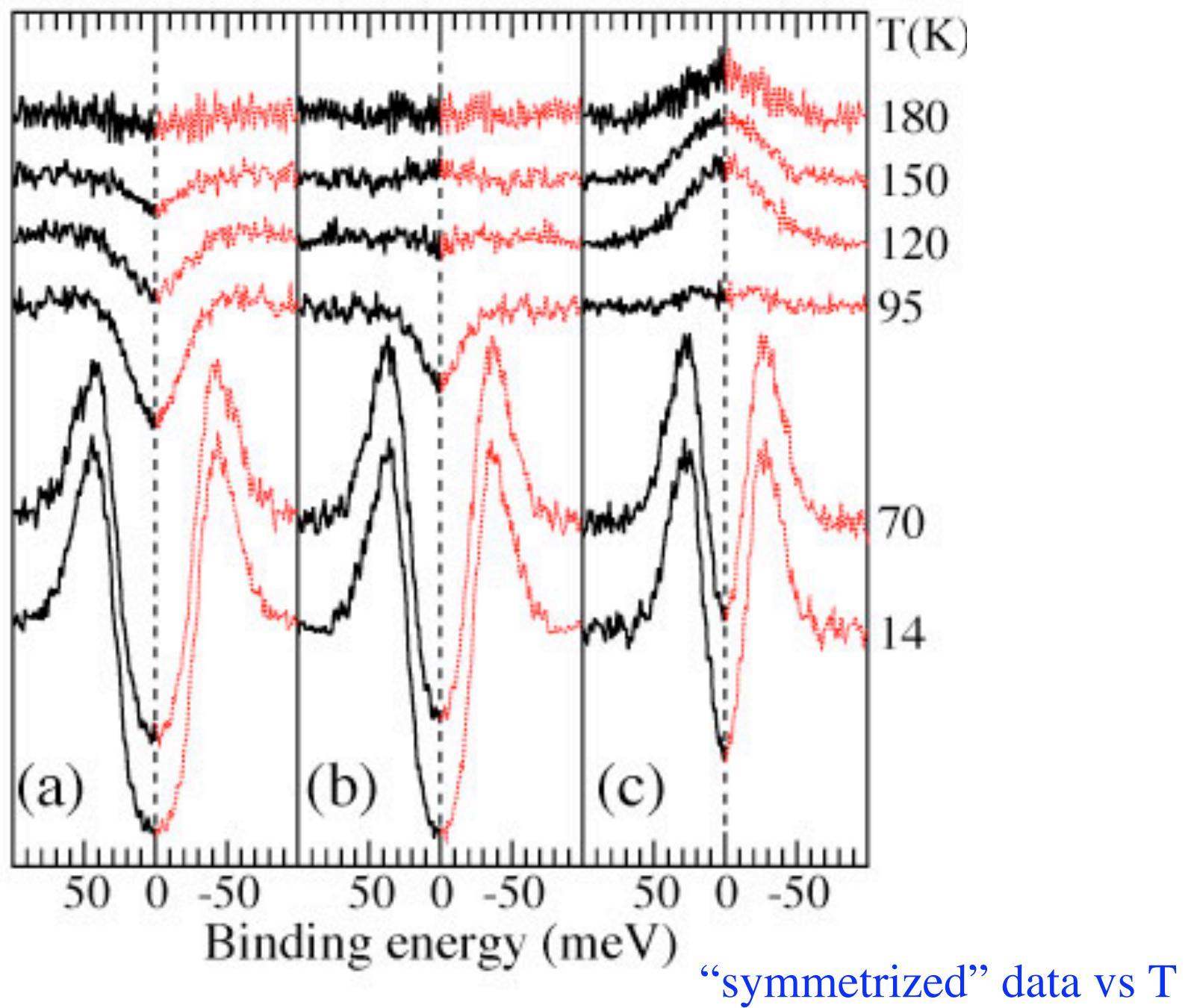


Underlying Fermi surface
for a gapped metal
(minimum gap locus - MGL)

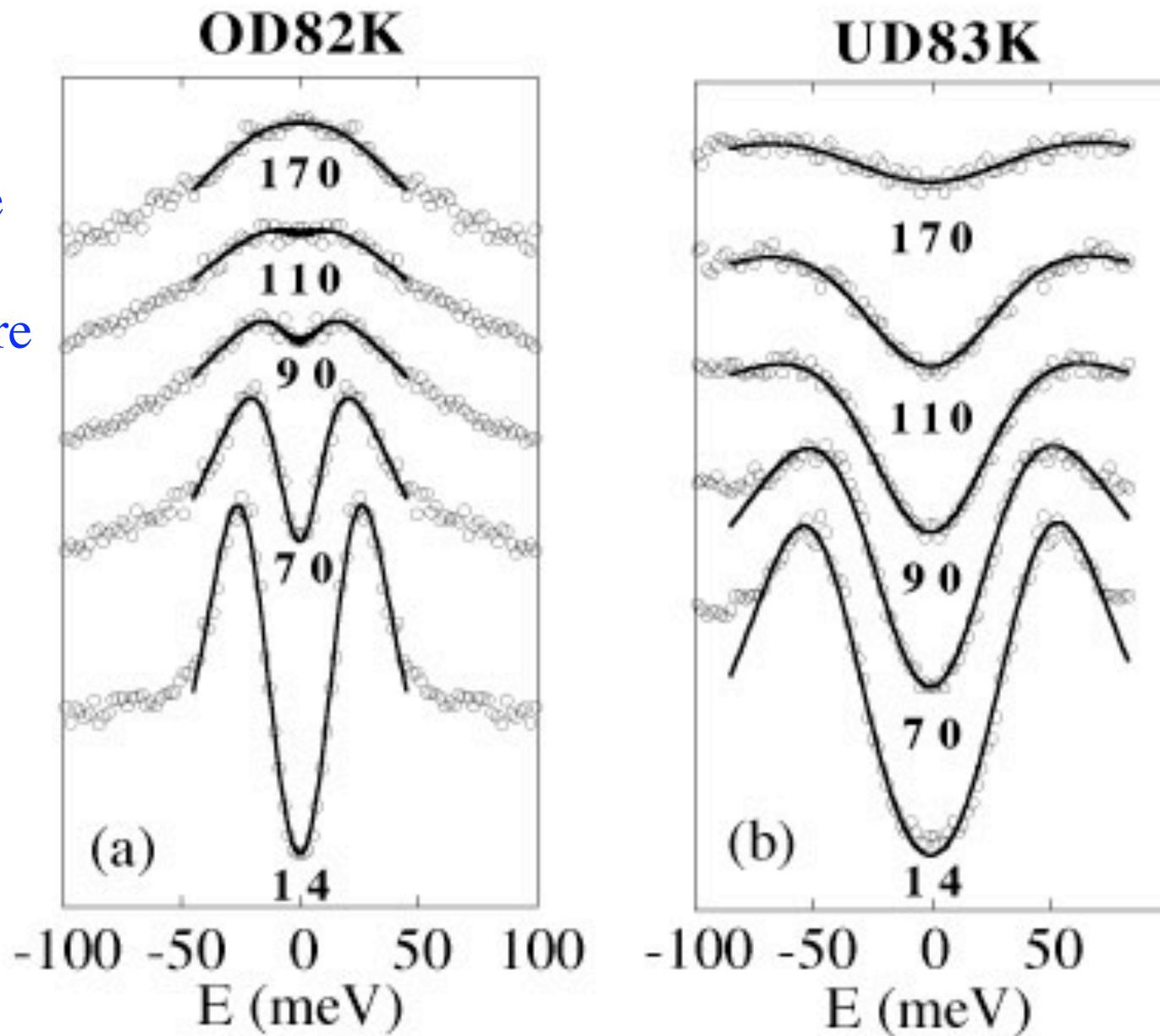
Find maximum in dispersion
along a given cut in \mathbf{k} space



Norman *et al.*, Nature 392, 157 (1998)

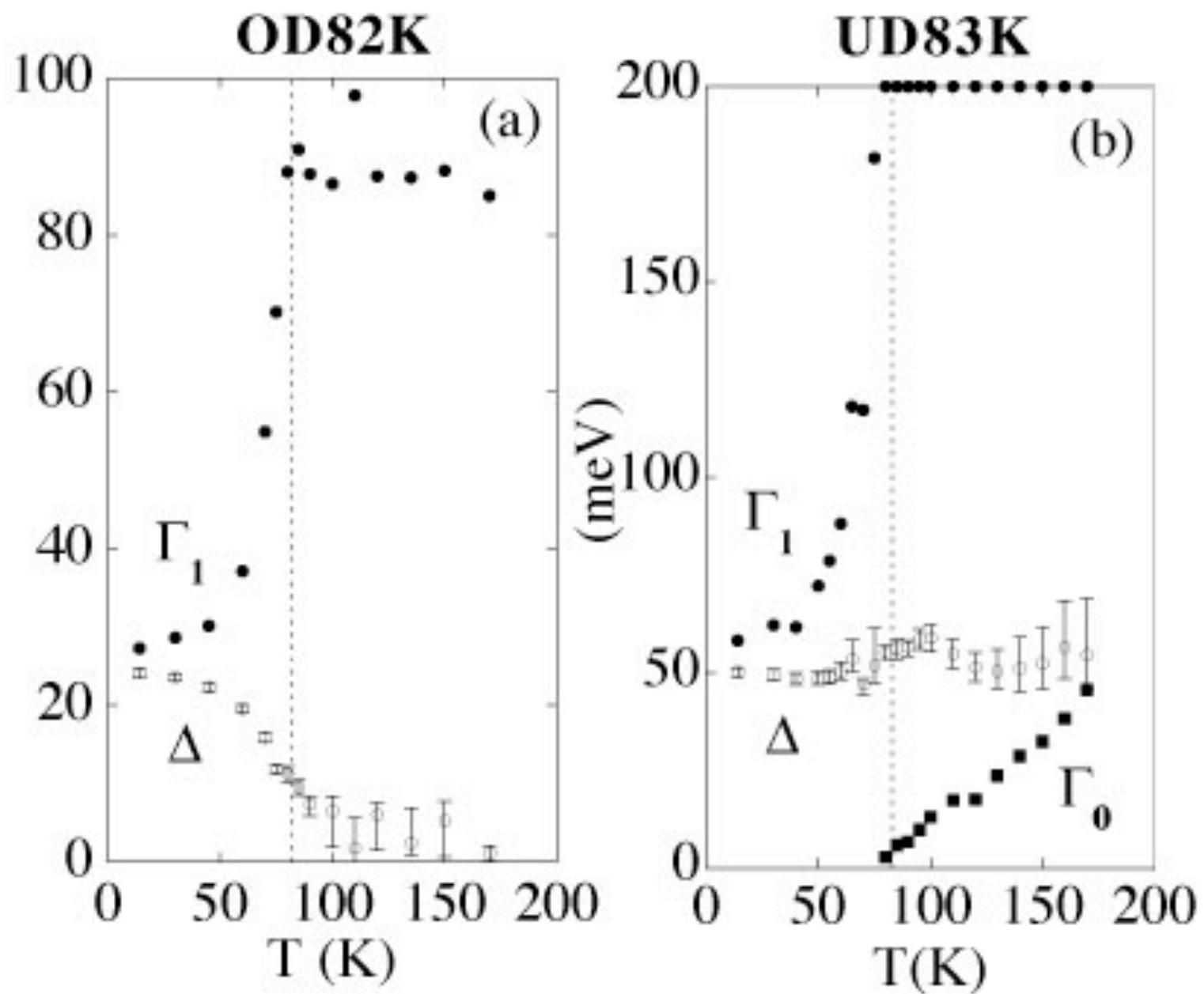


Antinode
vs
temperature

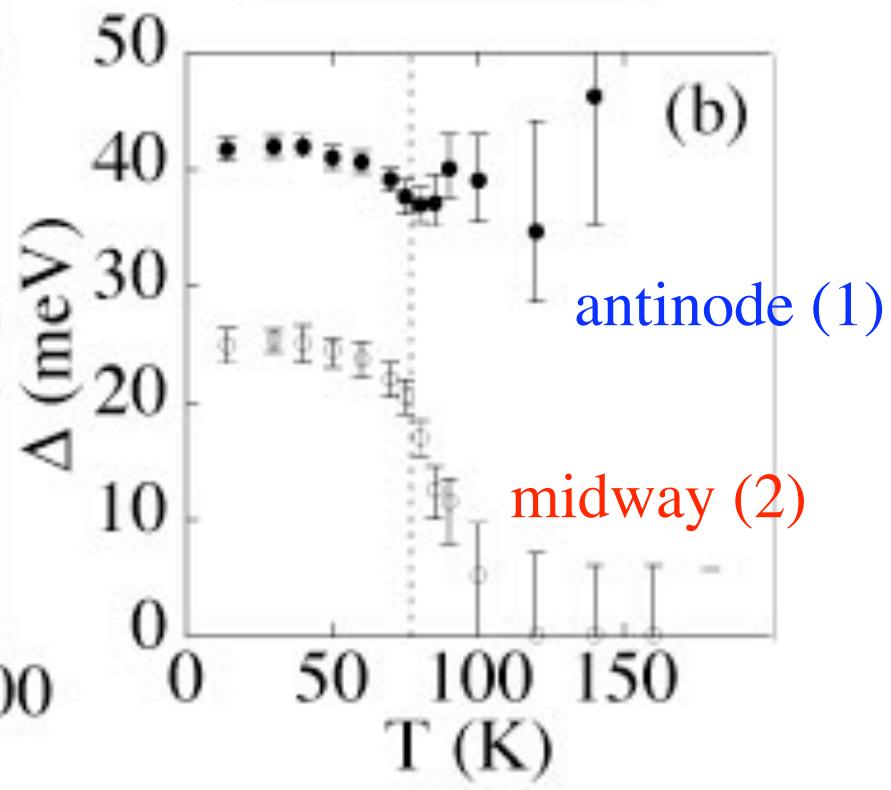
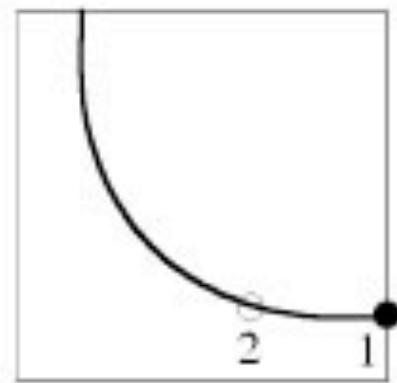
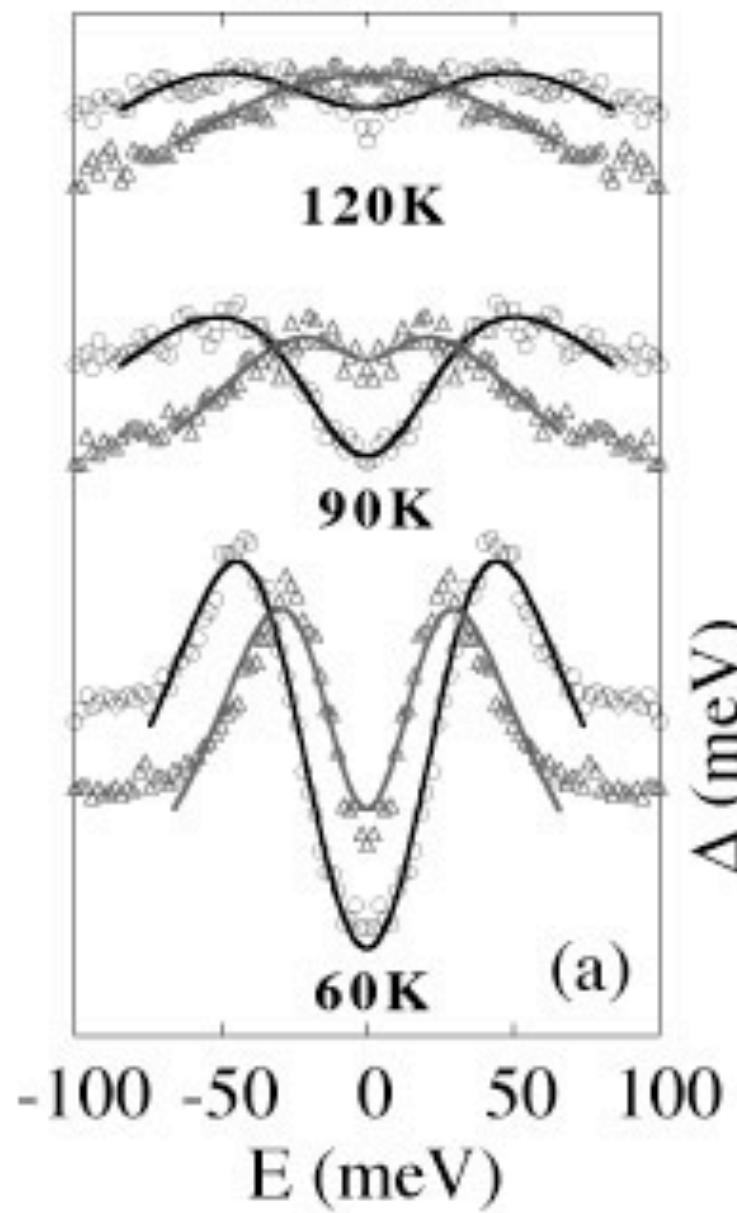


$$\Sigma = -i\Gamma_1 + \Delta^2/(\omega + i\Gamma_0)$$

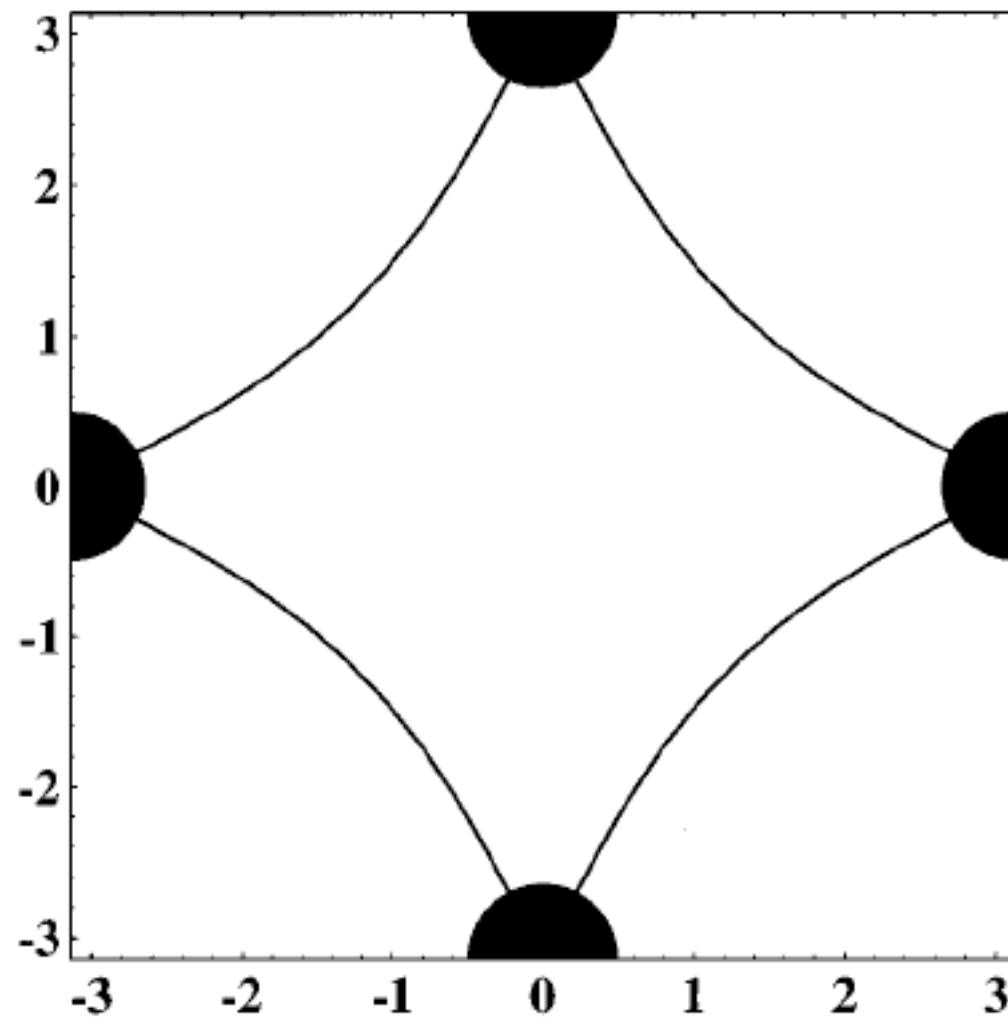
Norman *et al.*, Phy Rev B 57, 11093 (1998)



UD77K



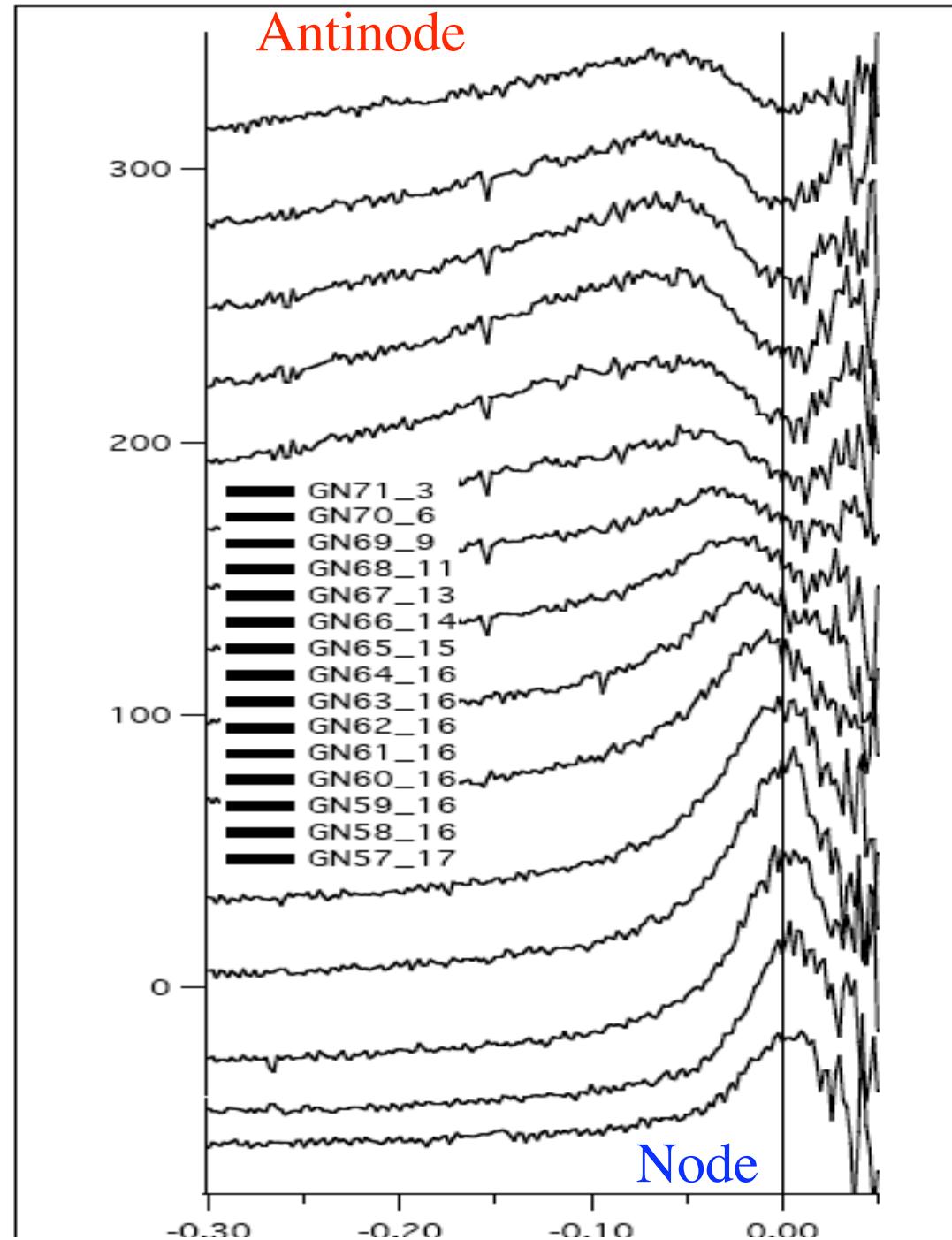
Arcs Connecting Pseudogapped Regions



Geshkenbein, Ioffe, Larkin - Phys Rev B 55, 3173 (1997)

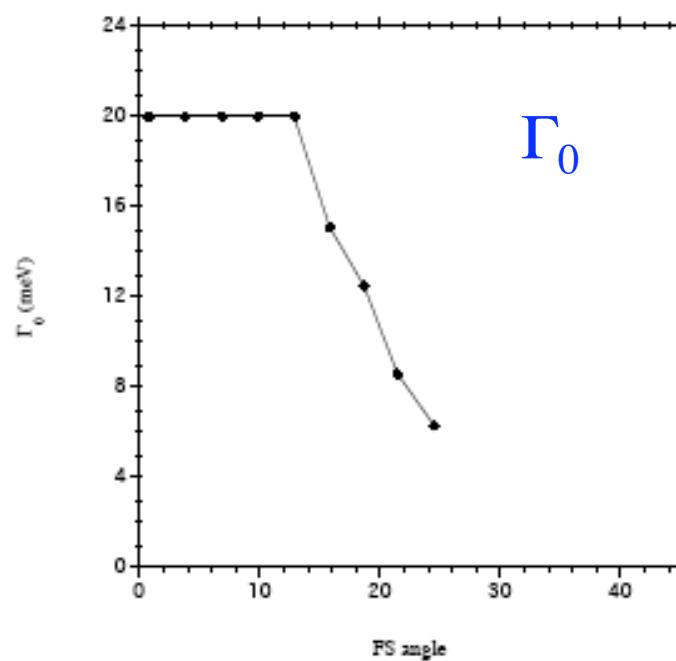
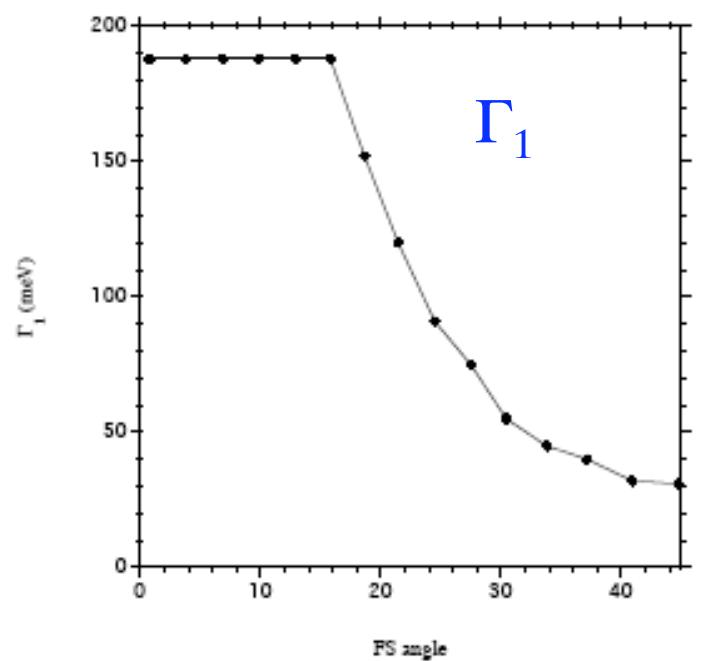
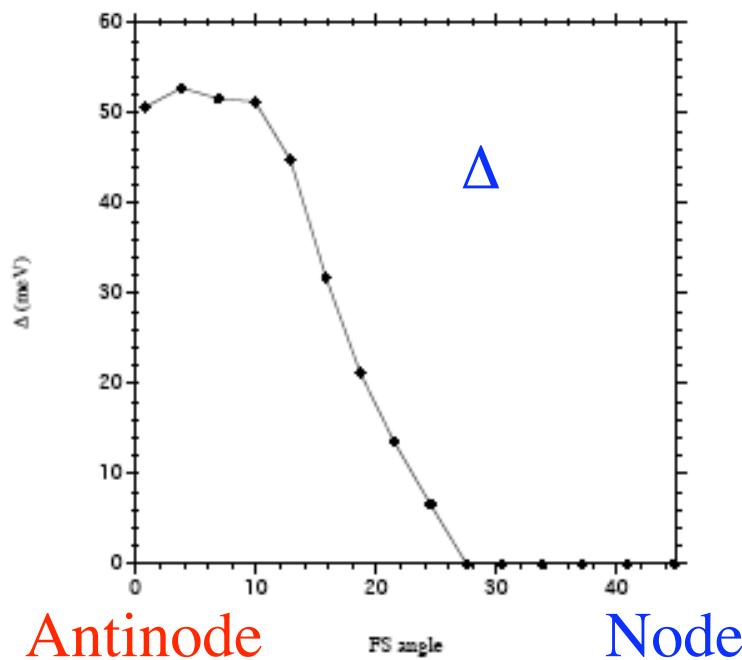
Bi2212
OP90K
T=140K

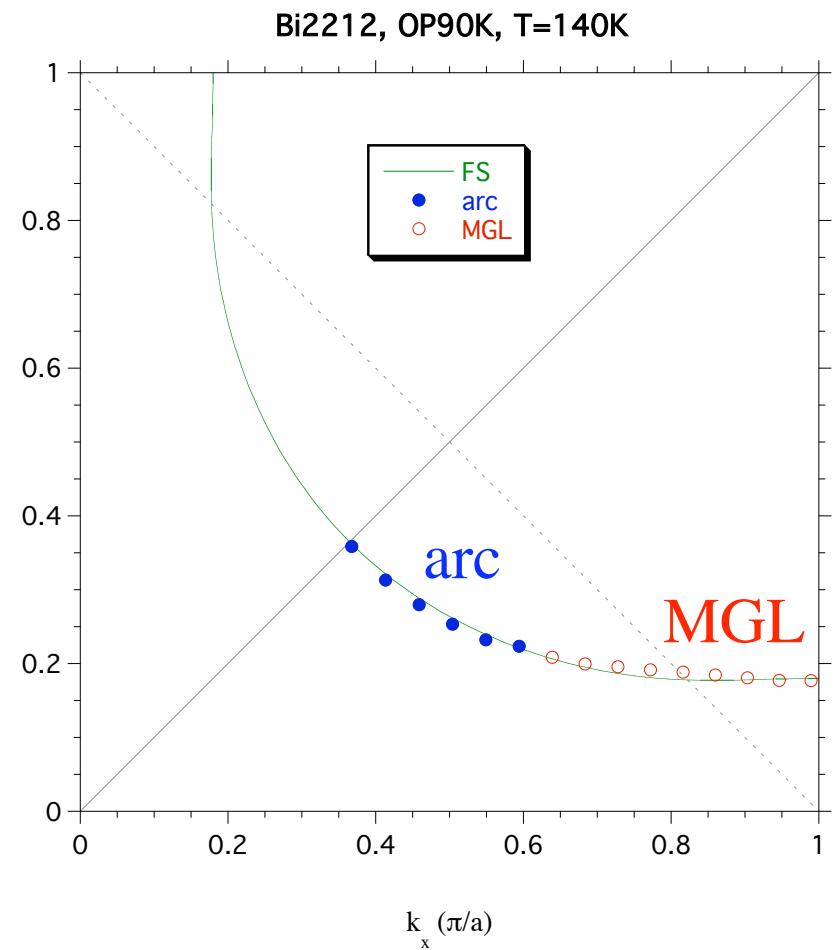
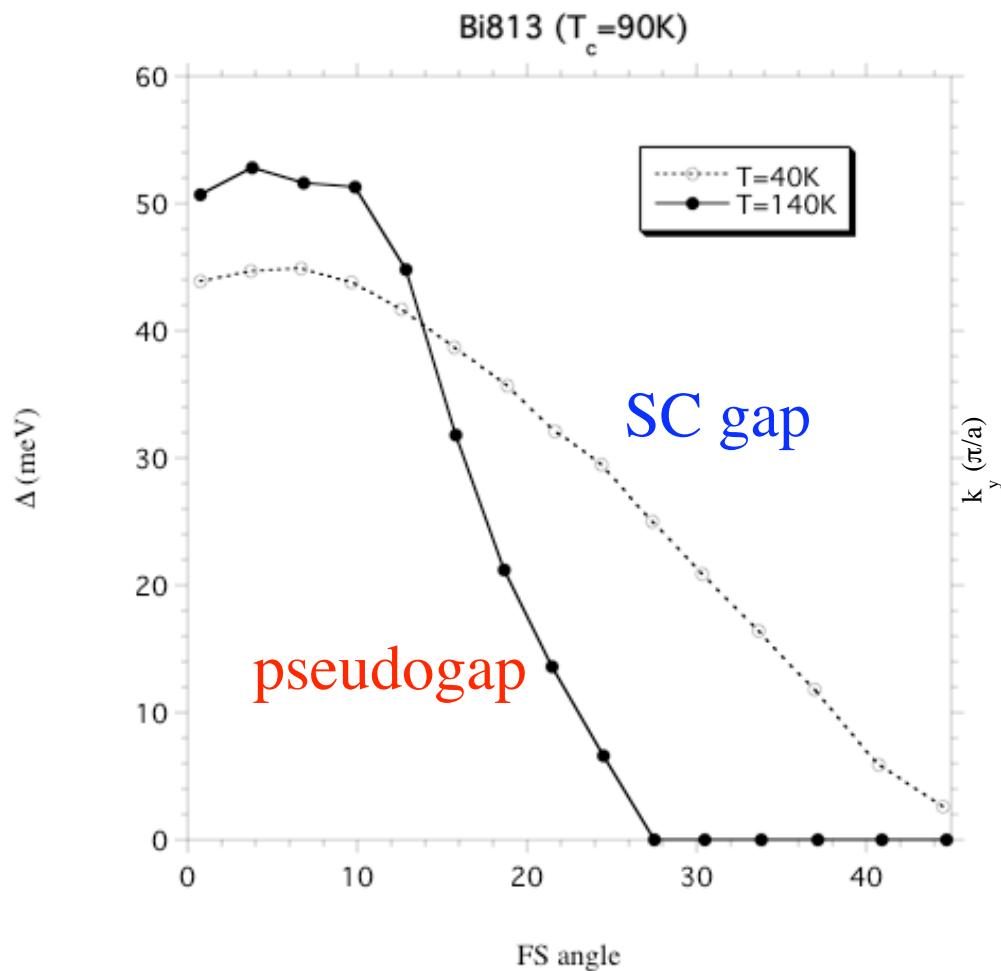
Fermi function
divided data



Bi2212 OP90K
T=140K vs
Fermi surface angle

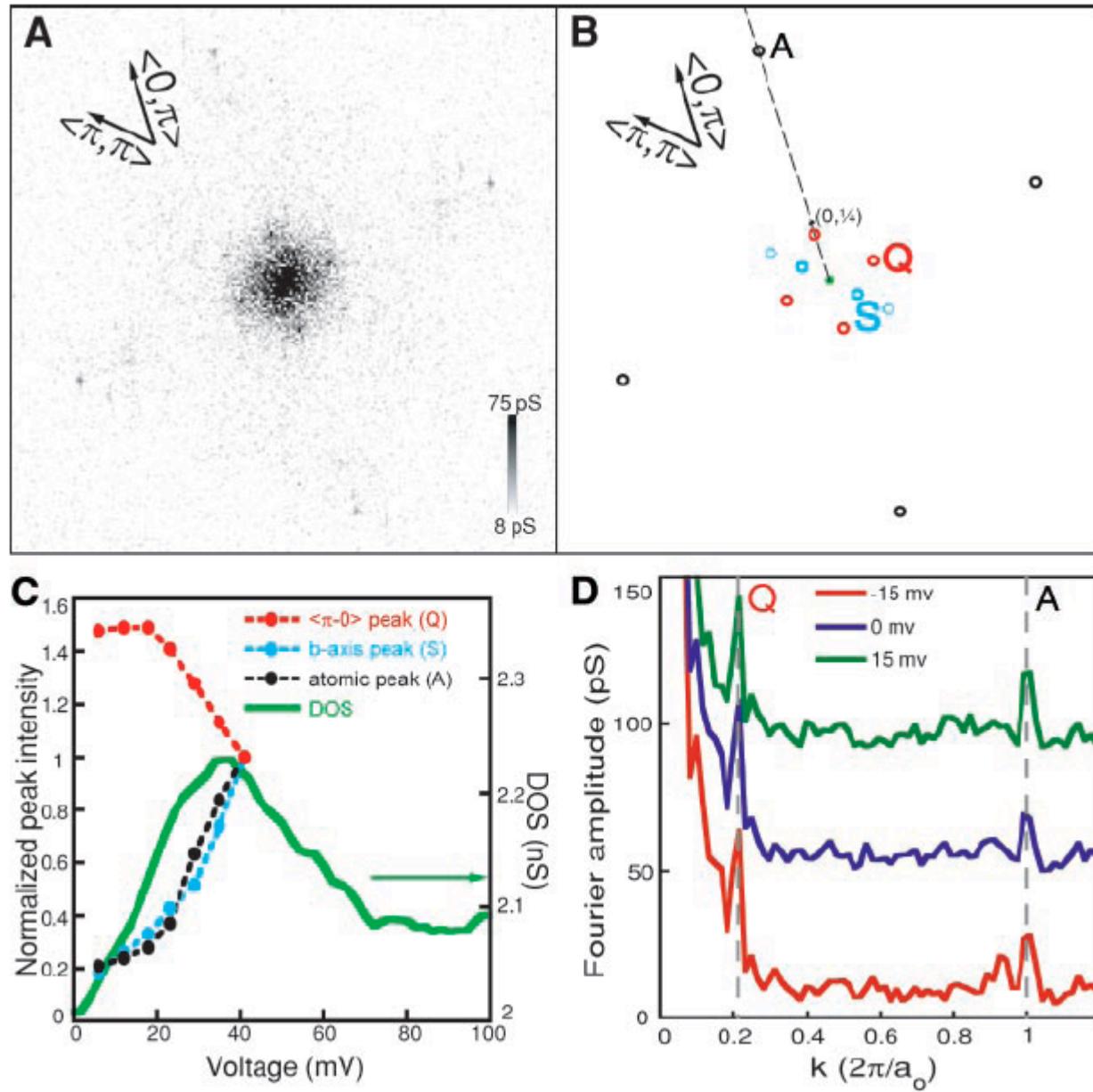
$$\Sigma = -i\Gamma_1 + \Delta^2/(\omega + i\Gamma_0)$$



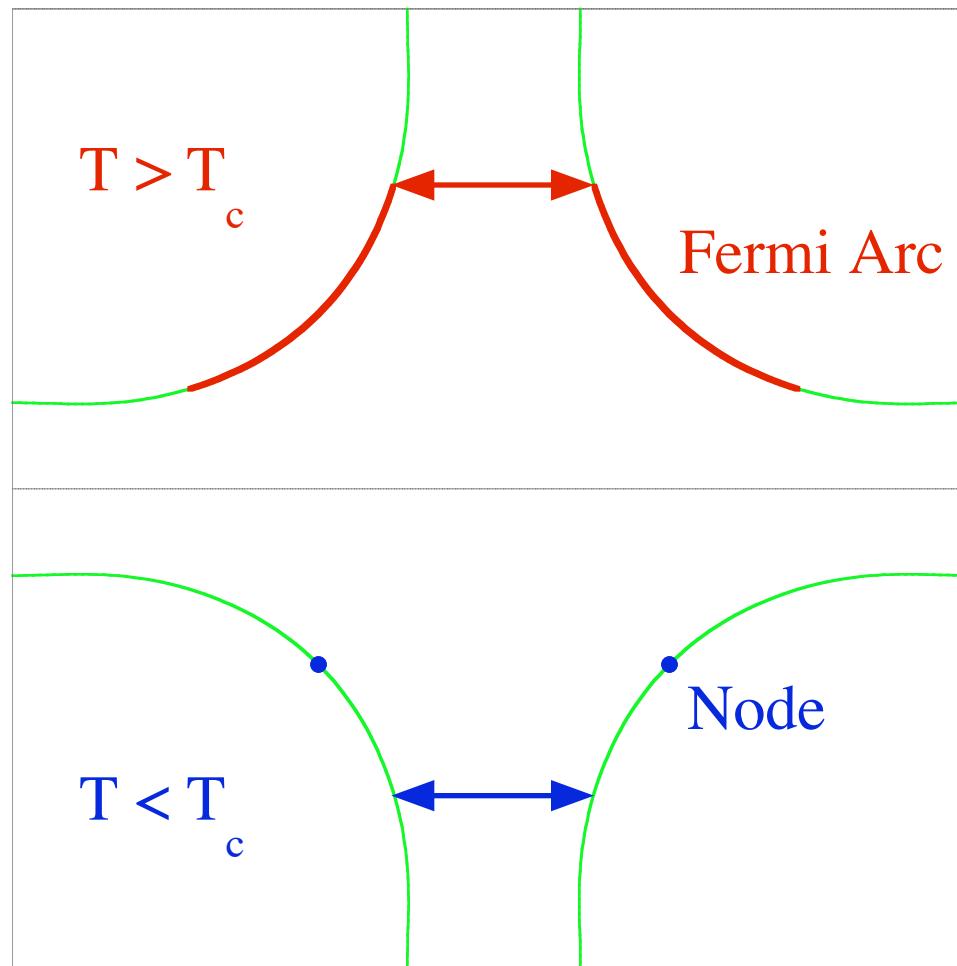


Non-dispersive FT-STM peaks in the pseudogap state

Vershinin *et al.*, Science 303, 1995 (2004) - Charge ordering?

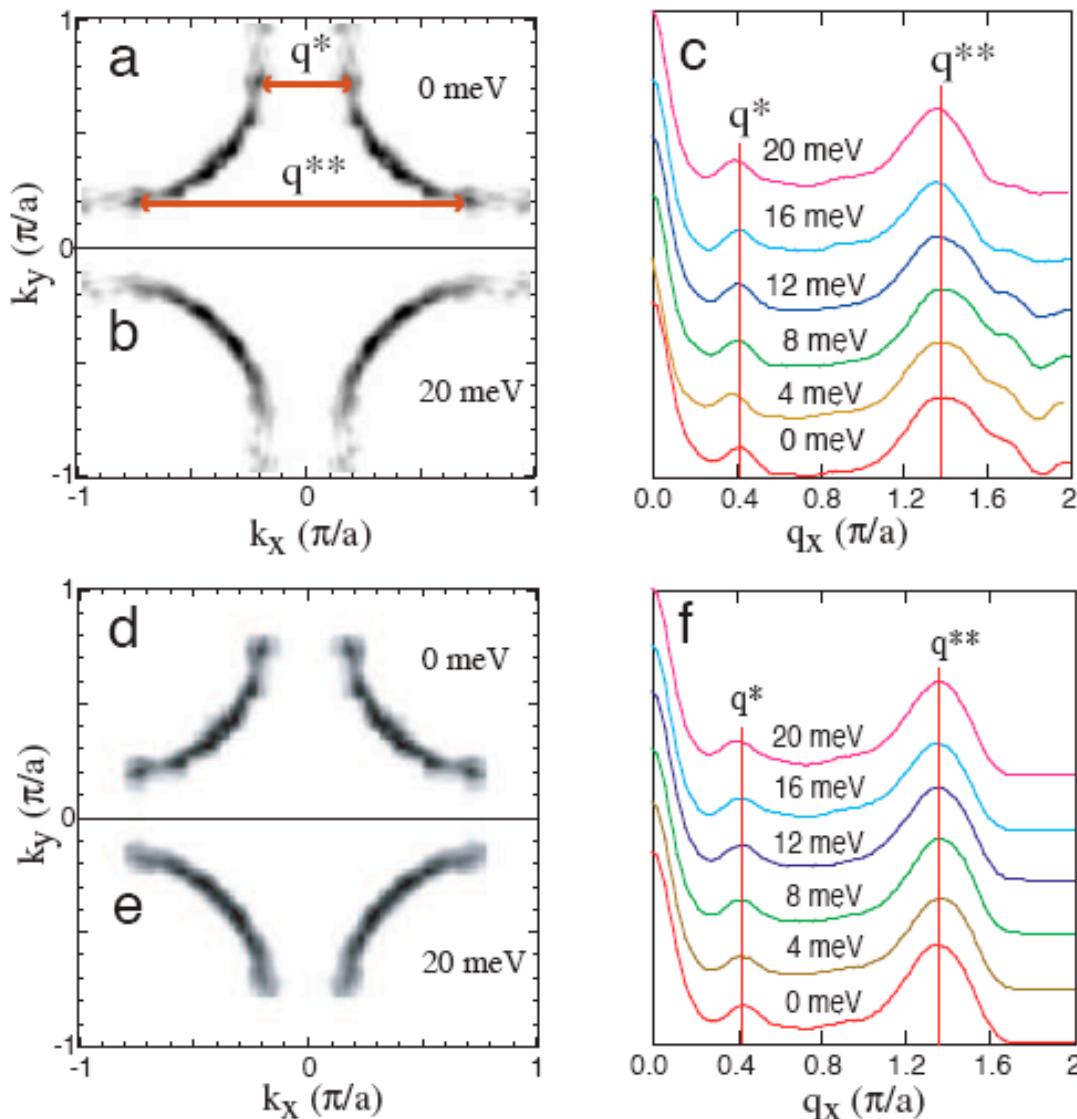


STM Fourier wavevector connects the tips of the Fermi arc

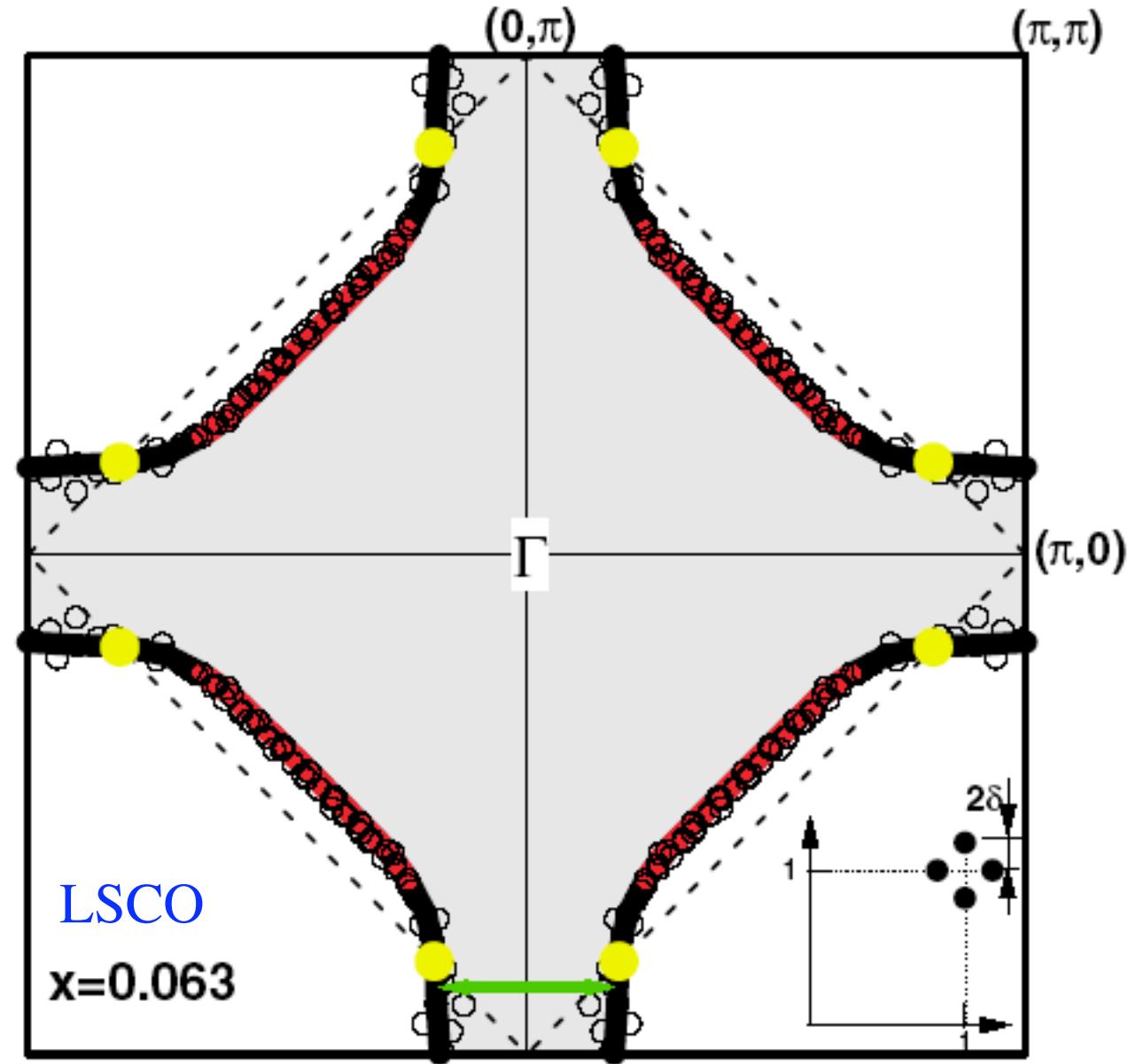


cartoon - Norman, Science 303, 1985 (2004)

ARPES autocorrelation sees this wavevector



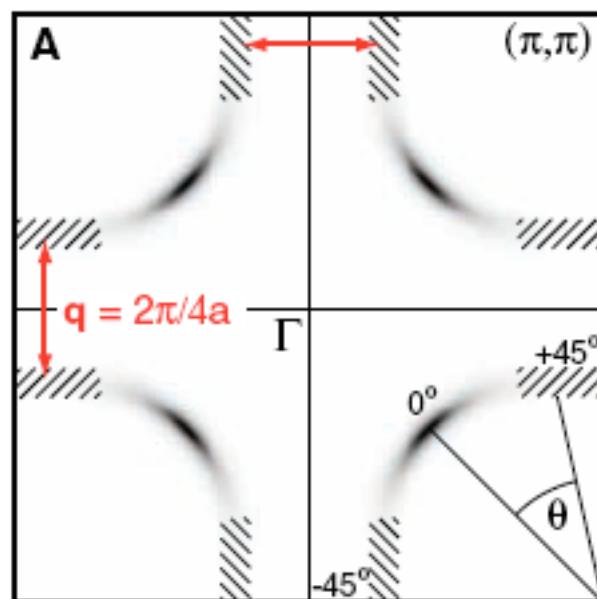
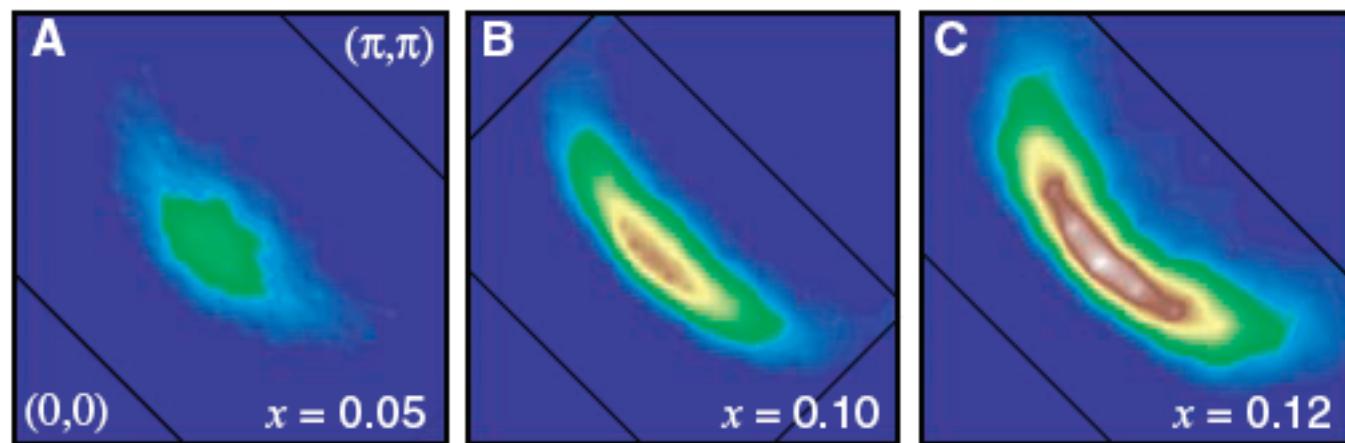
Chatterjee *et al.*, Phys. Rev. Lett. 96, 107006 (2006)



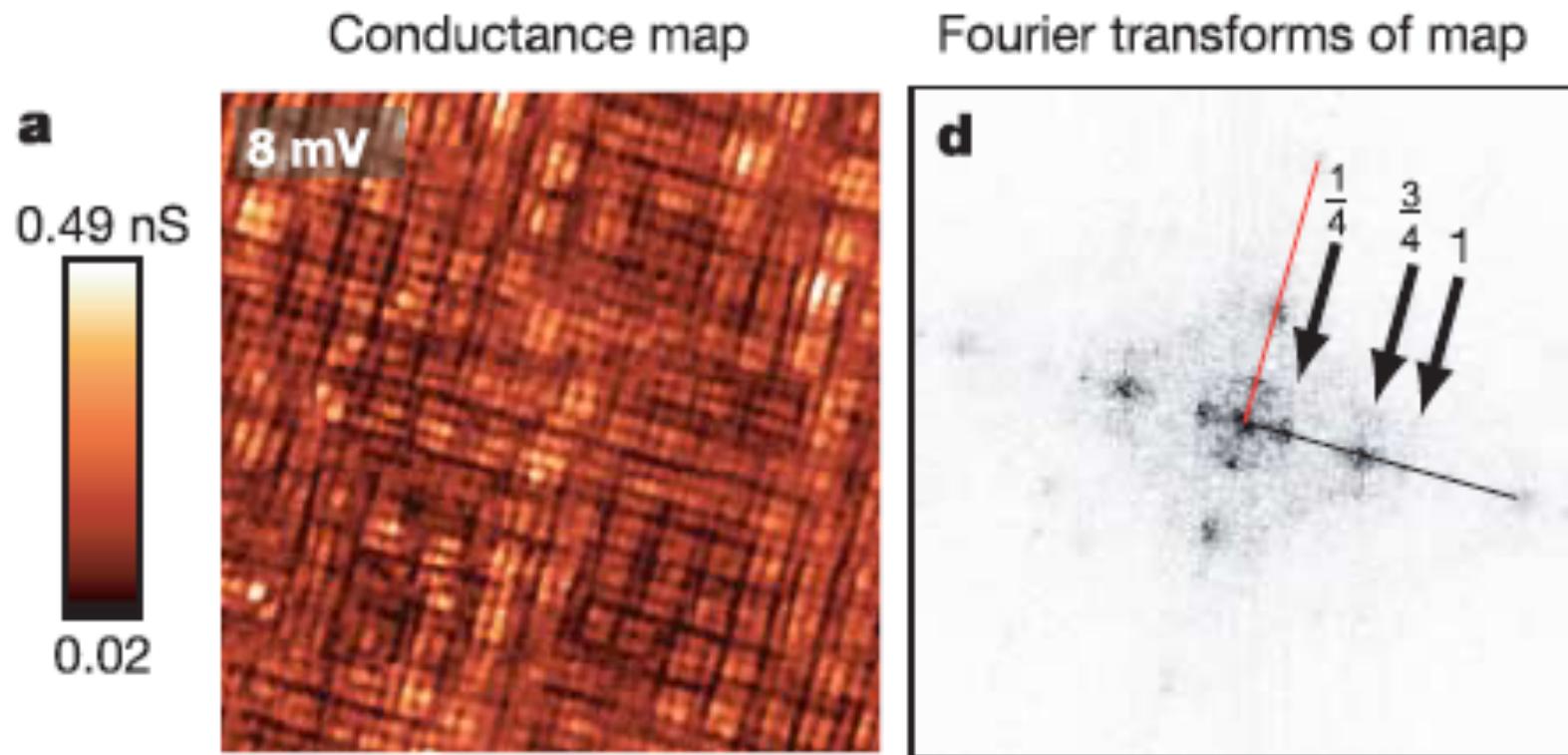
Zhou *et al.*, PRL 92, 187001 (2004) --> nested Fermi surface in LSCO

Antinodal Charge Ordering in $\text{Ca}_{2-x}\text{Na}_x\text{CuO}_2\text{Cl}_2$

Shen *et al*, Science 307, 901 (2005)

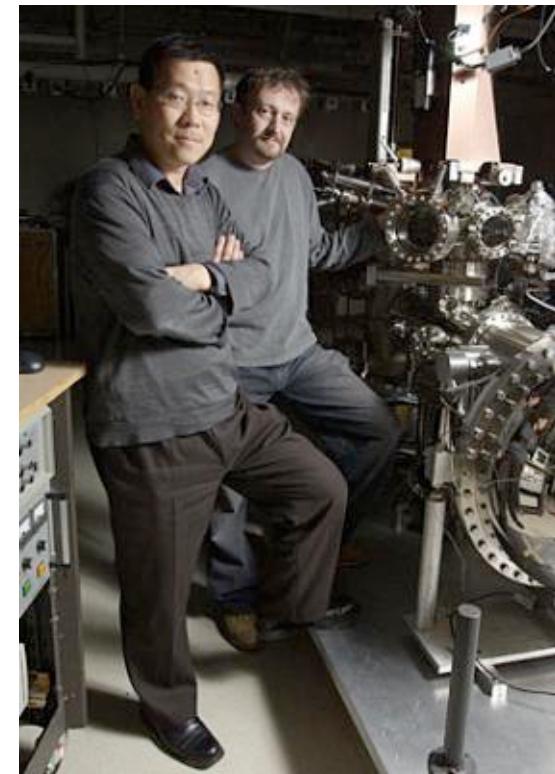
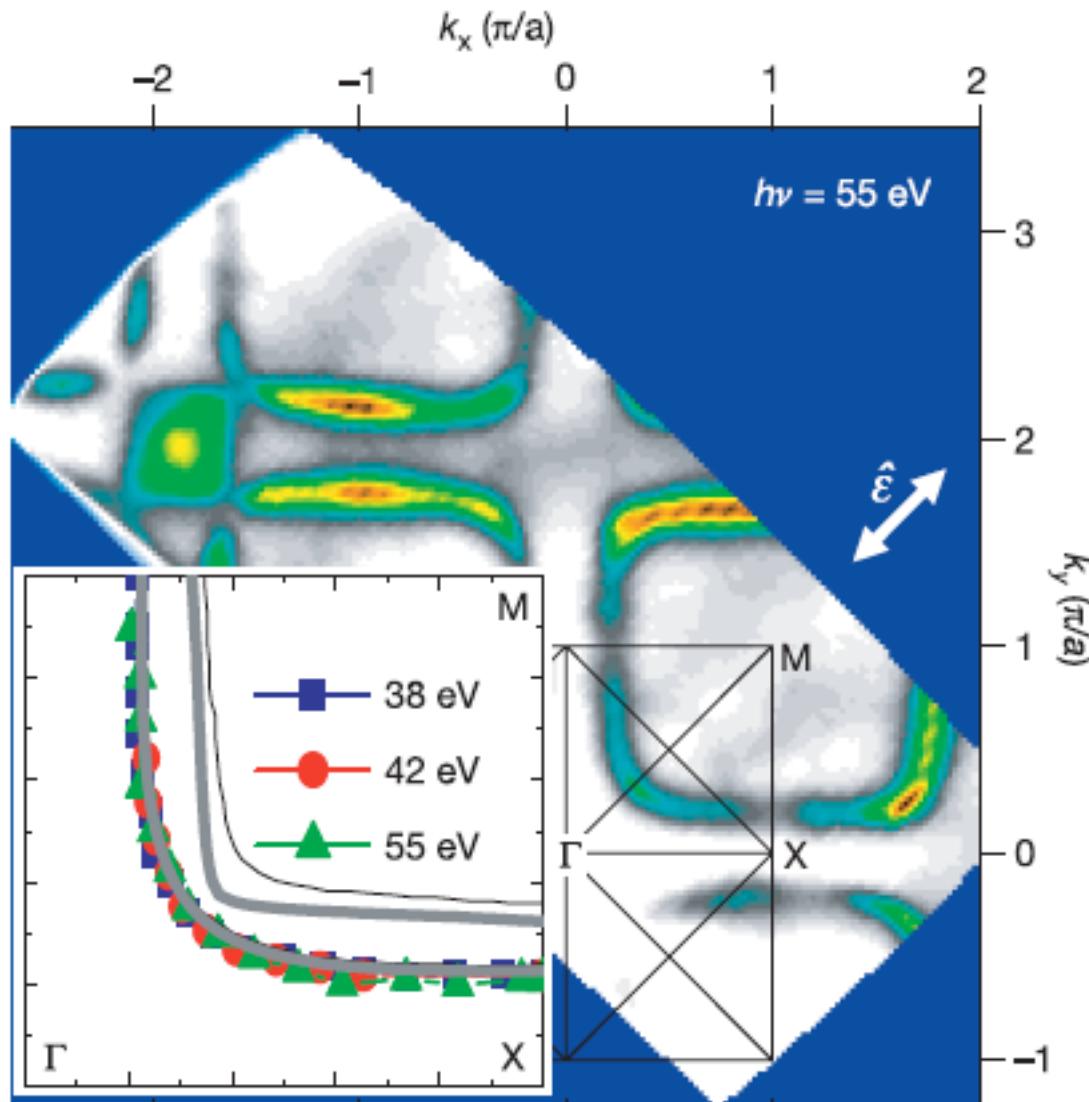


‘Checkerboard’ Charge Ordering in $\text{Ca}_{2-x}\text{Na}_x\text{CuO}_2\text{Cl}_2$

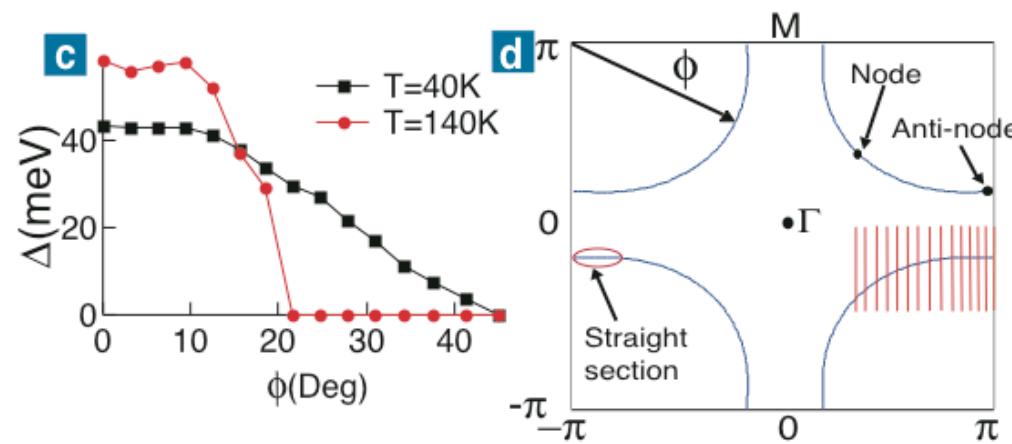
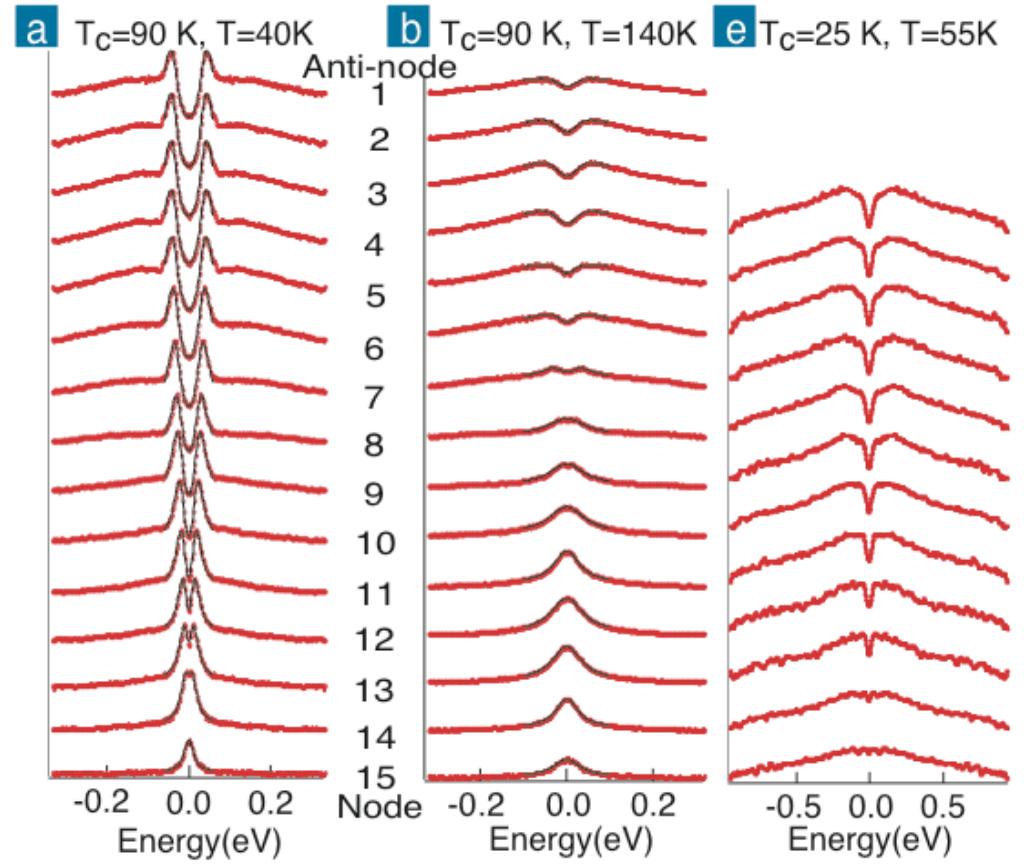


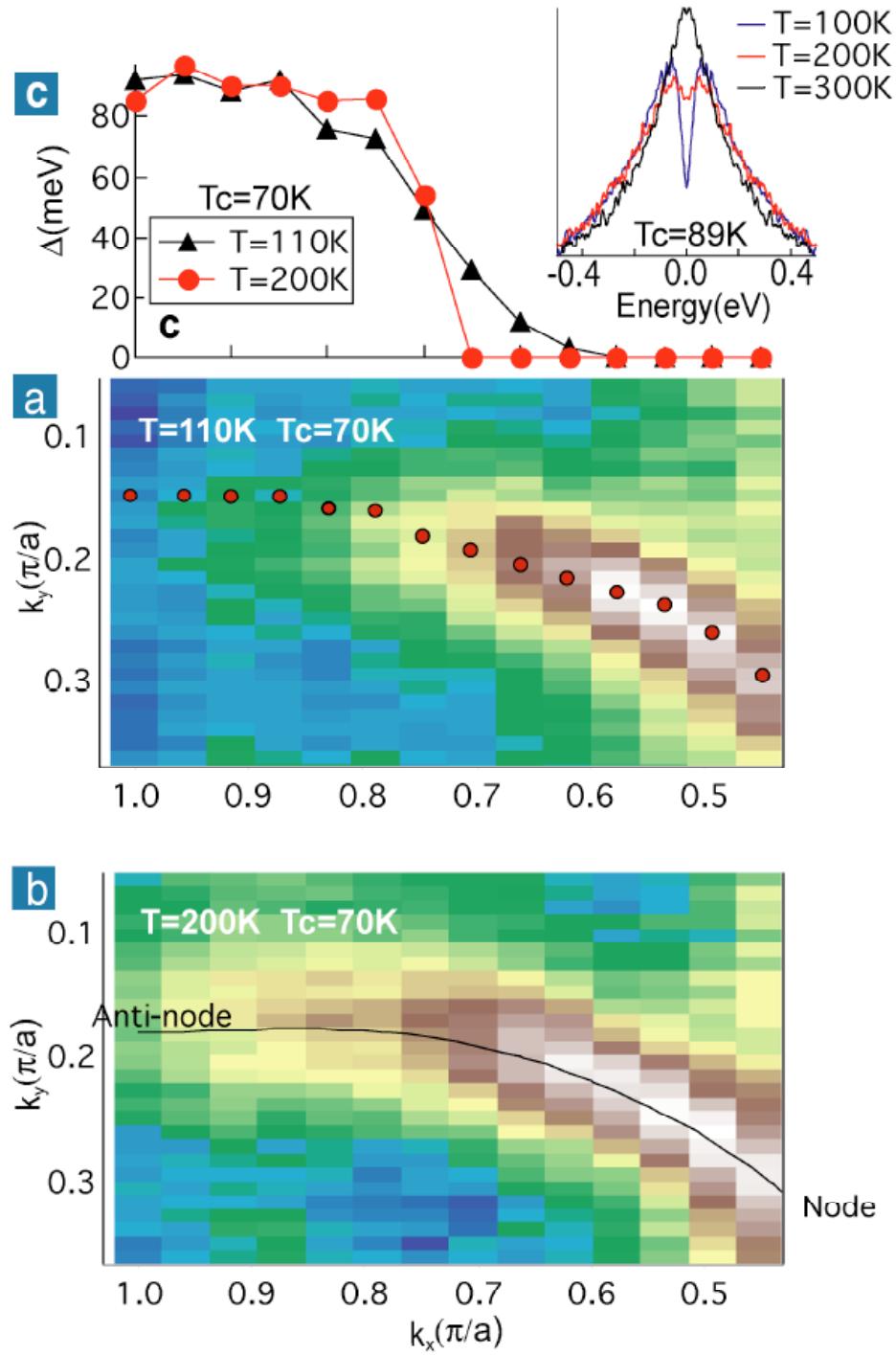
Hanaguri *et al*, Nature 430, 1001 (2004)

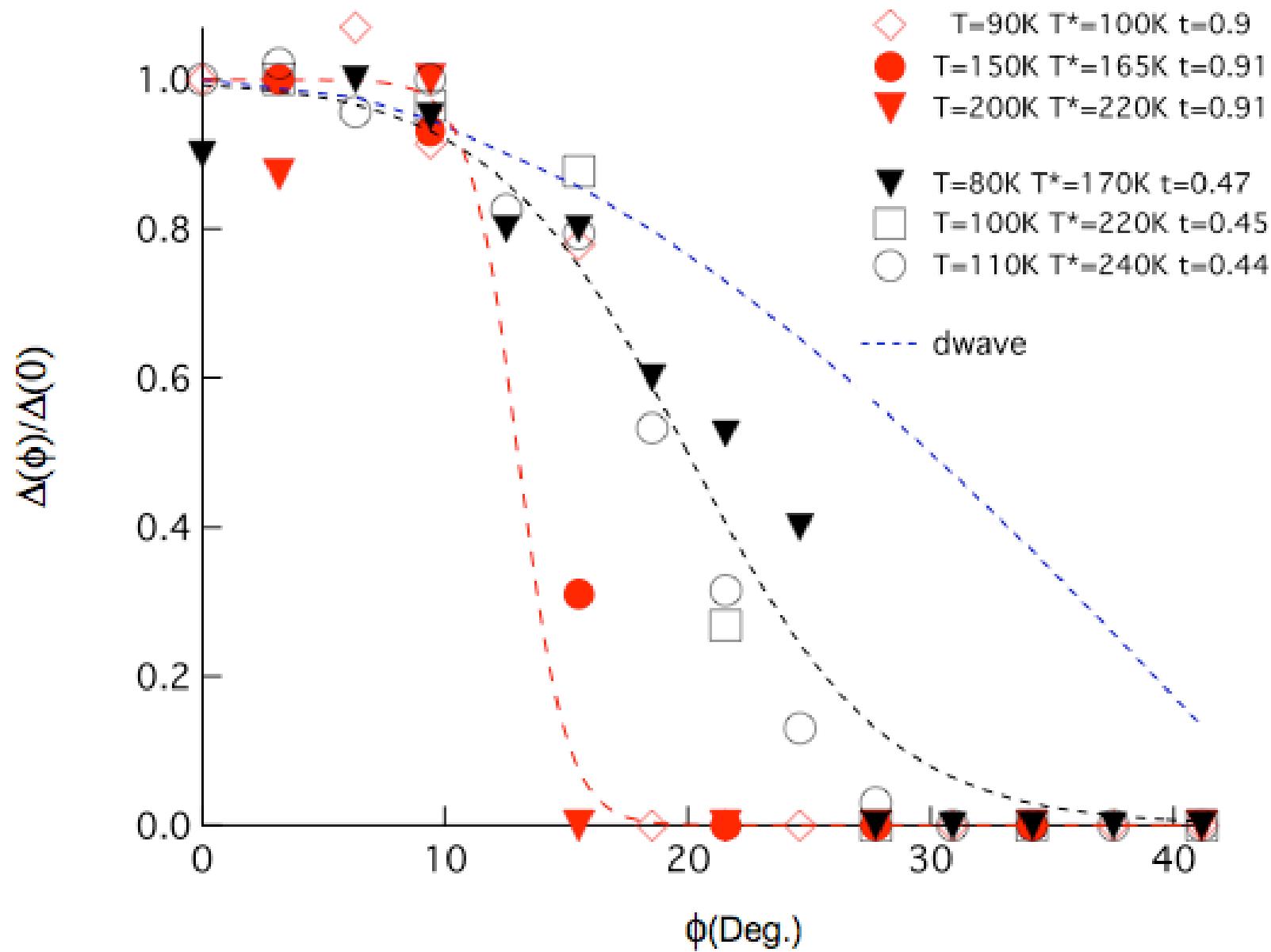
Experiments debunk 'pseudogap' role in superconductivity

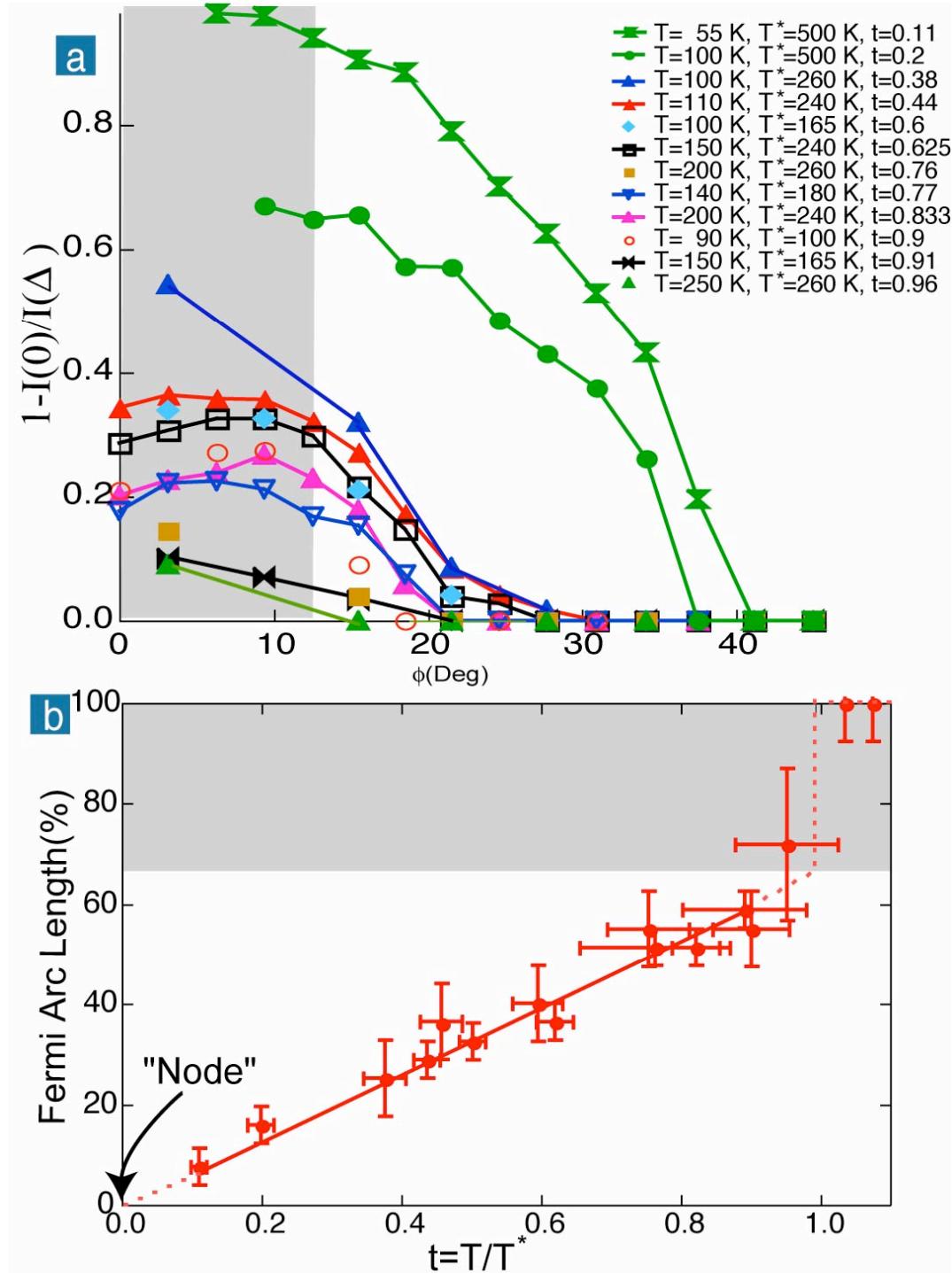


Pseudogap in Manganites - Mannella *et al.*, Nature 438, 474 (2005)

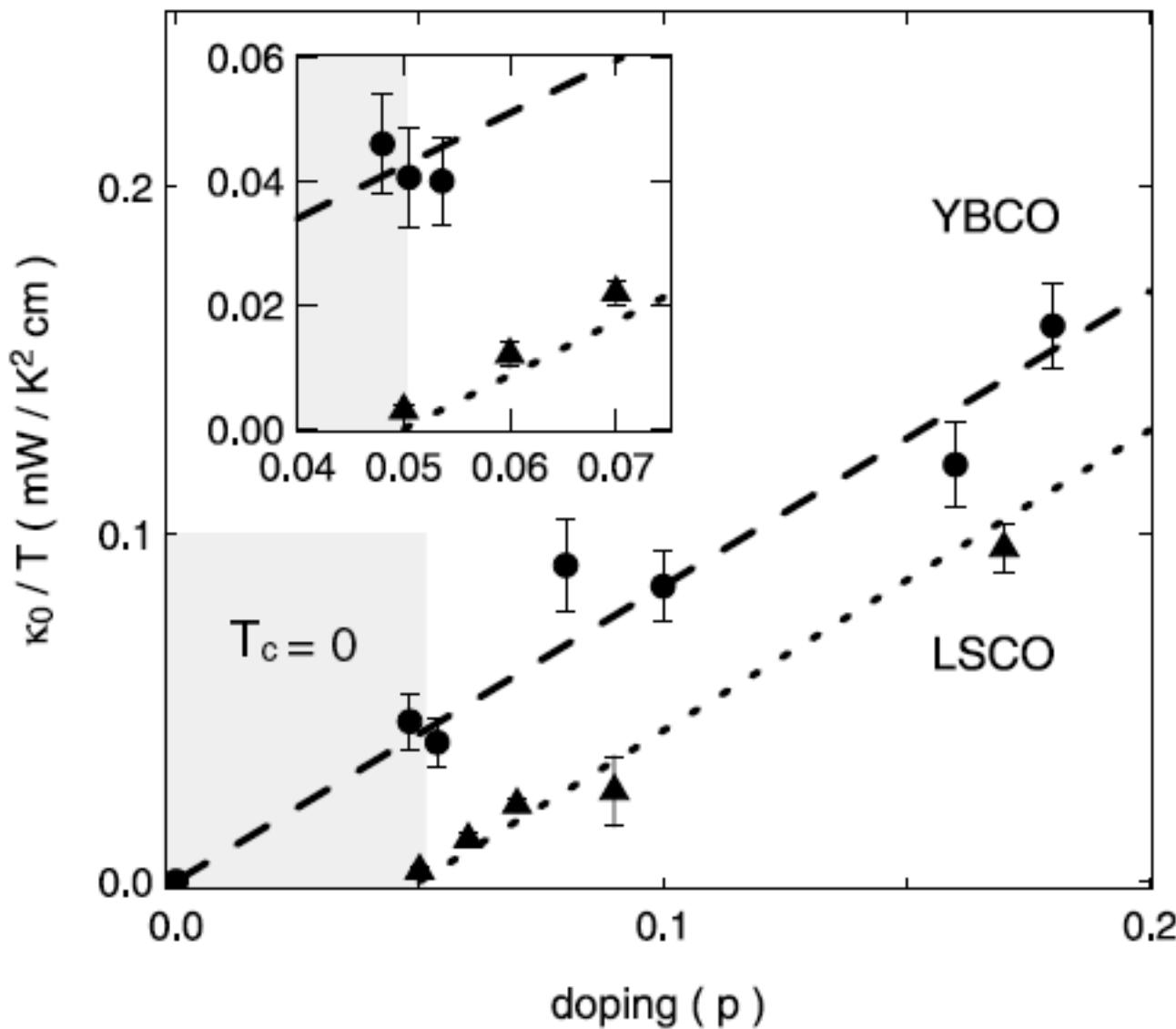






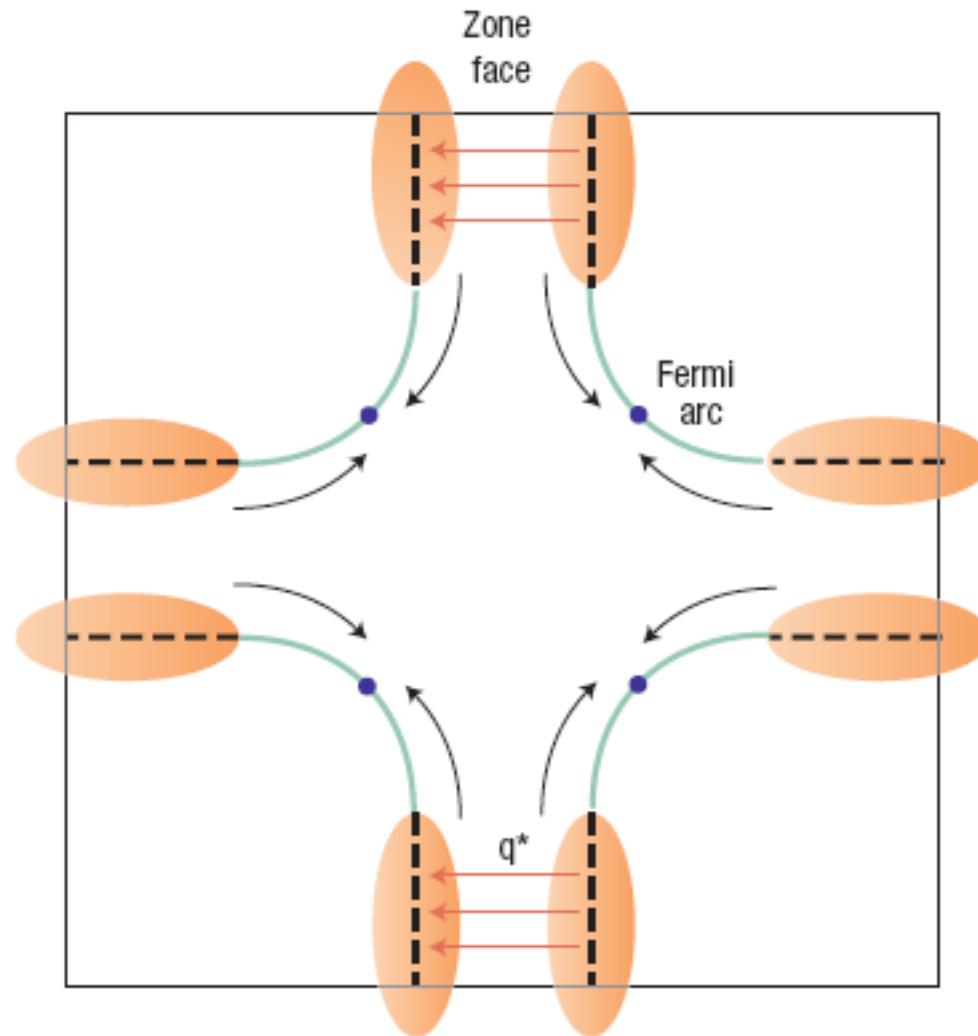


Nodal Liquid Implied by Low T Thermal Conductivity



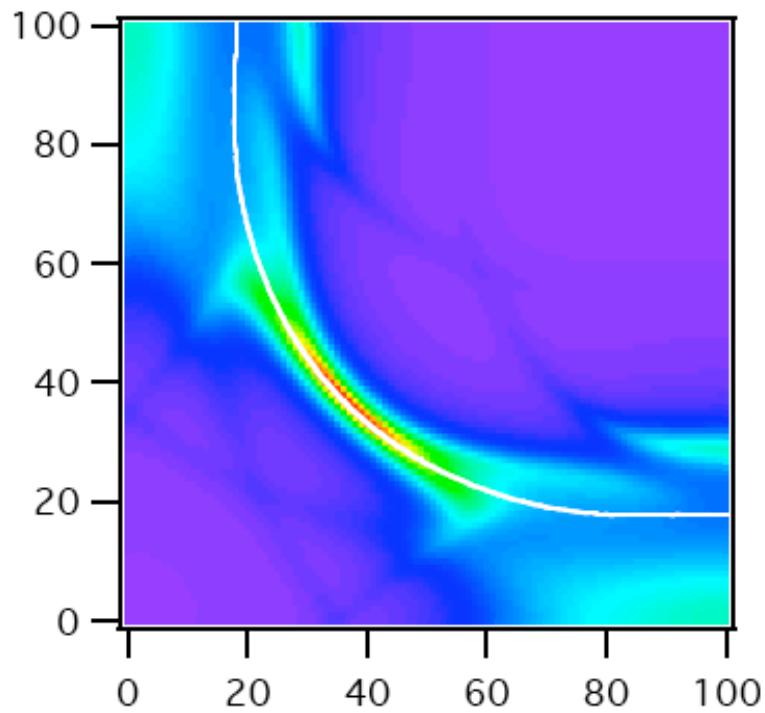
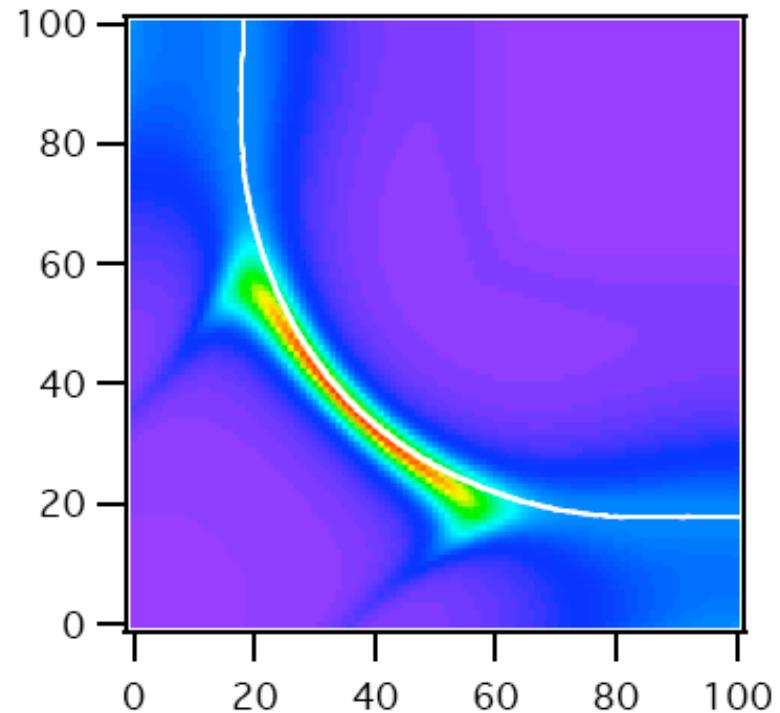
Sutherland *et al*, PRL 94, 147004 (2005)

Charge ordering?



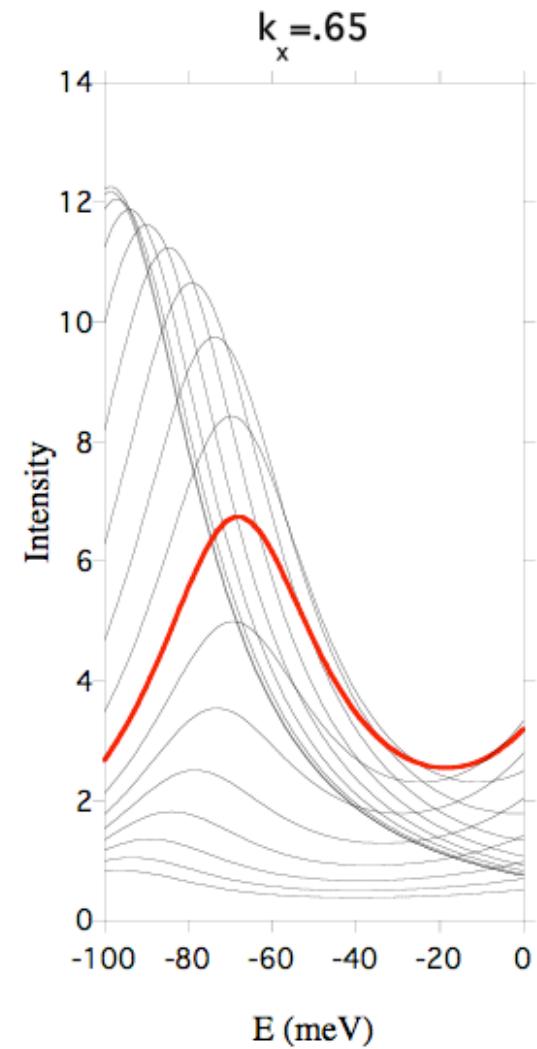
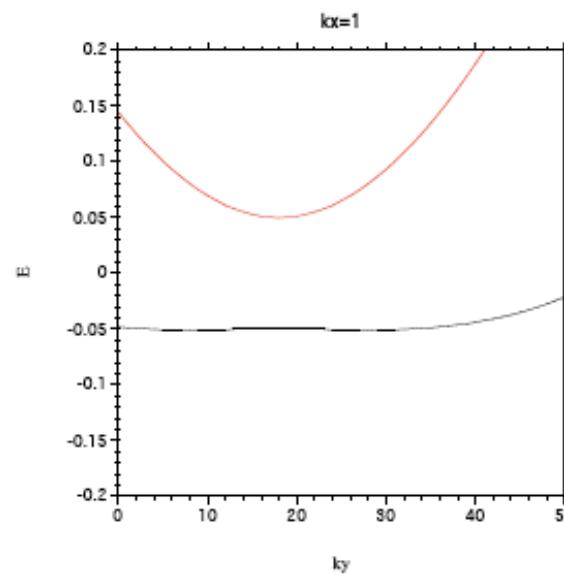
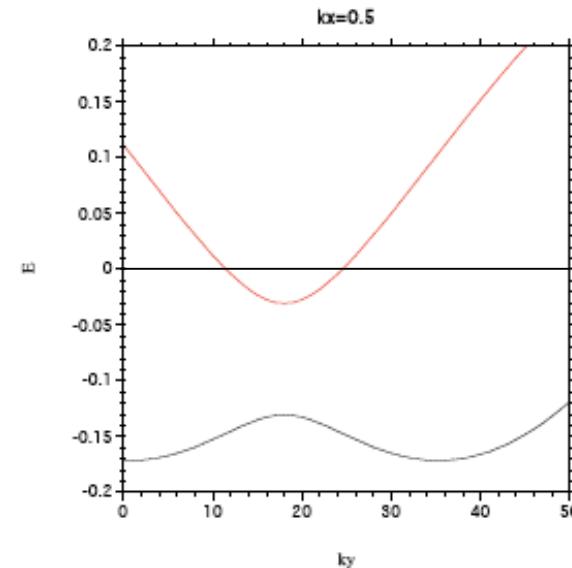
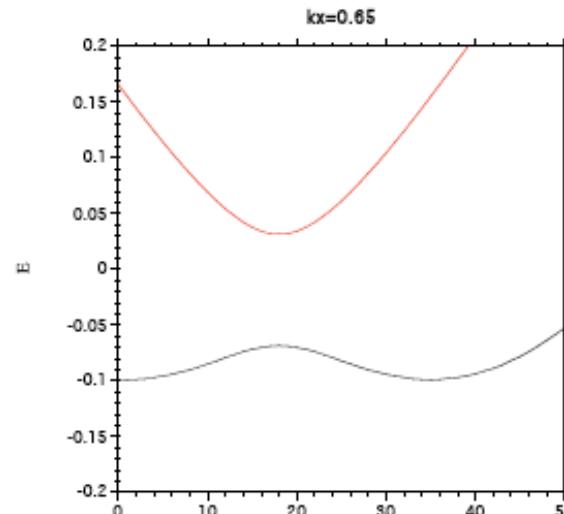
Kyle McElroy - Nature Physics 2, 441 (2006)

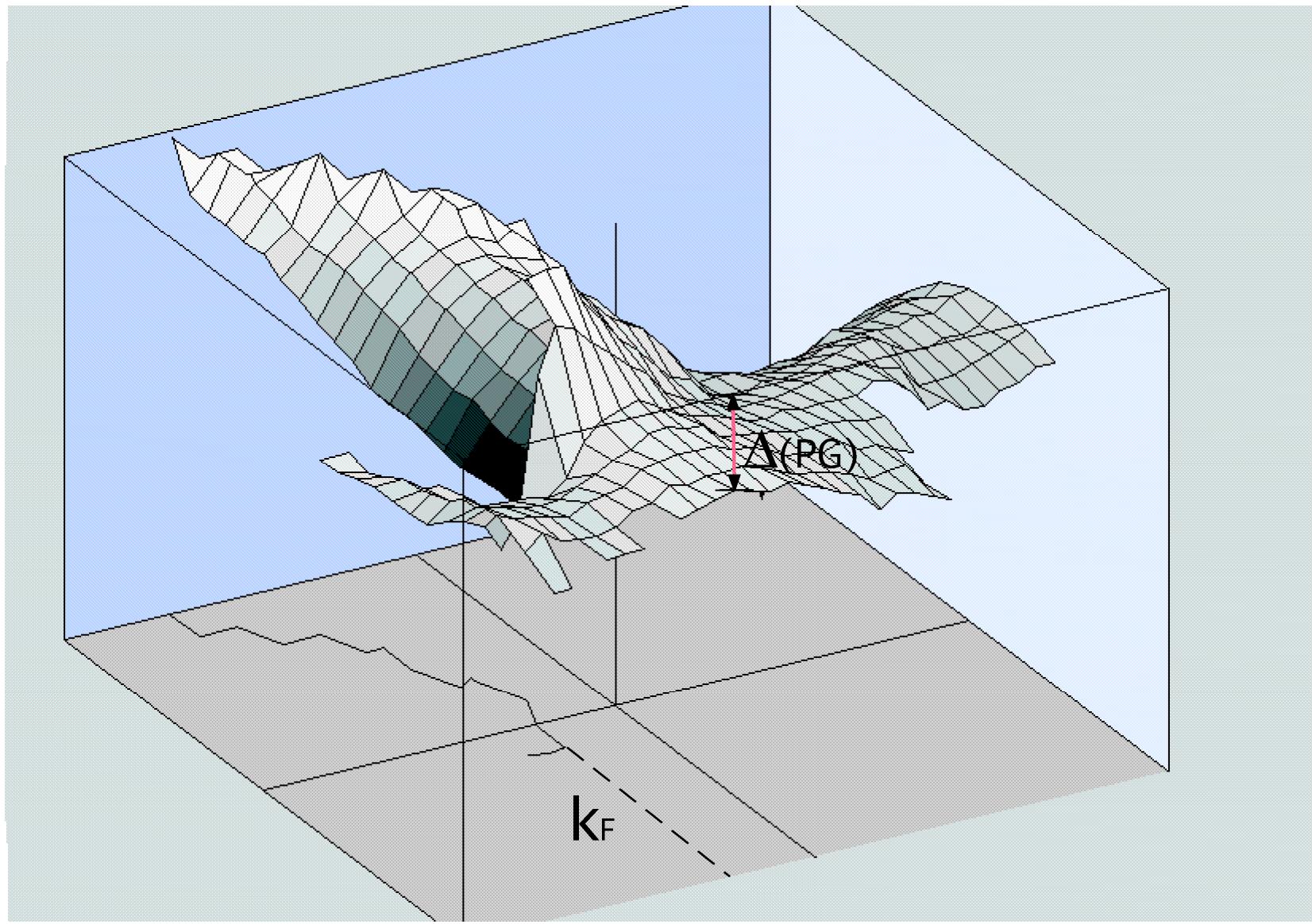
Charge ordering?



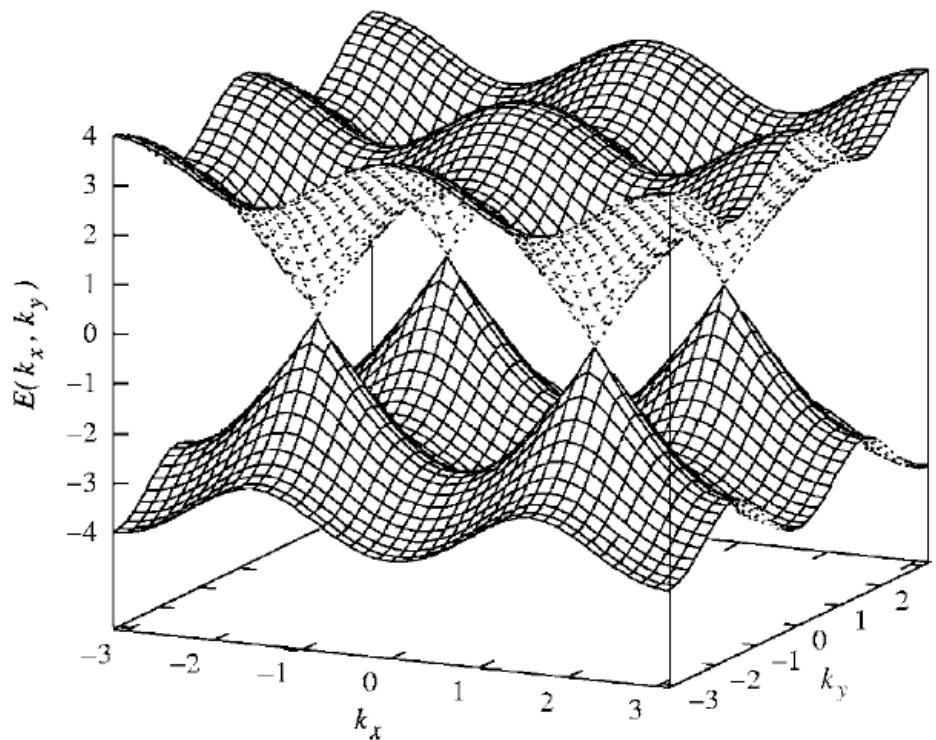
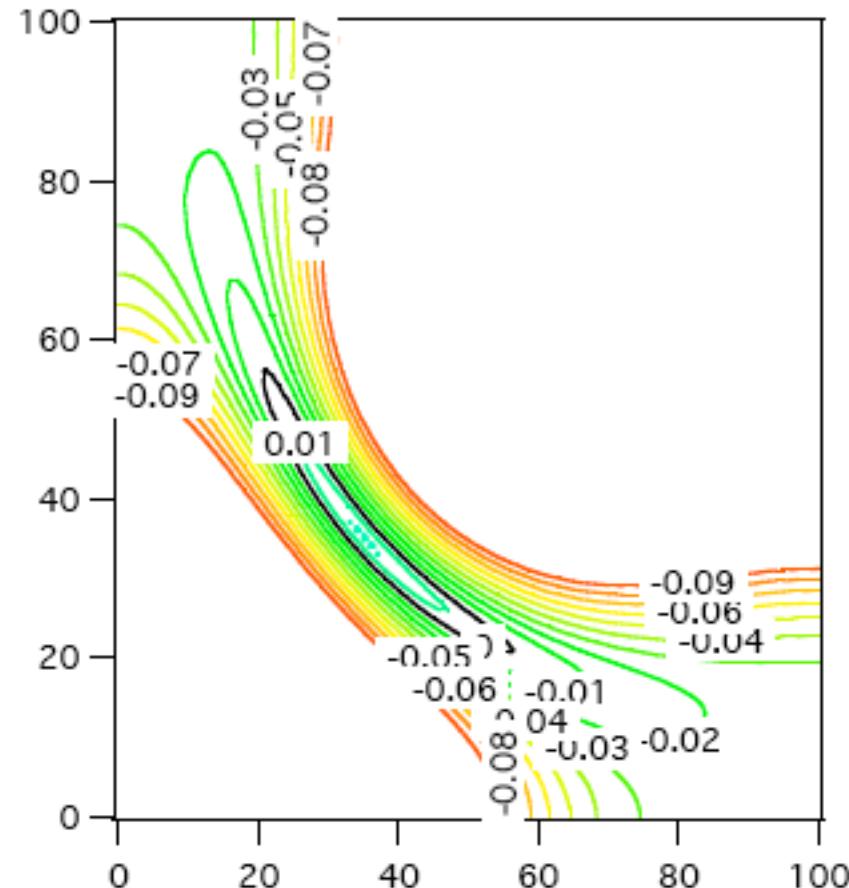
Zero energy intensity maps, left (\mathbf{q}) and right ($\mathbf{q}, -\mathbf{q}$)

Energy gap below E_F in the ‘arc’ region for charge ordering at finite q

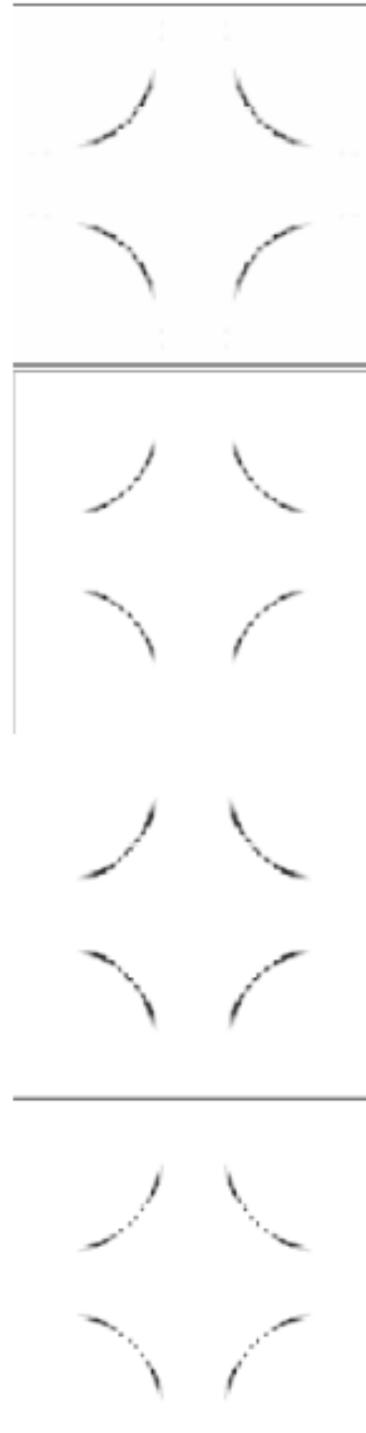




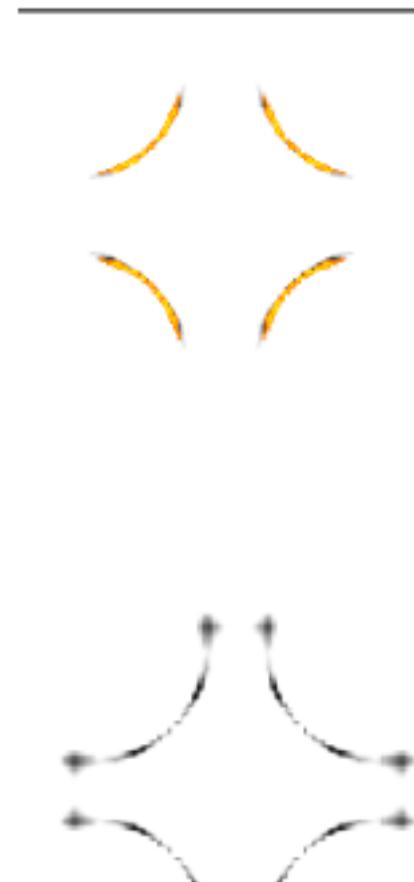
Dispersing Fermi Arcs in the Flux Phase State



Wen and Lee - Phys Rev Lett 80, 2193 (1998)



Fermi arcs dispersionless

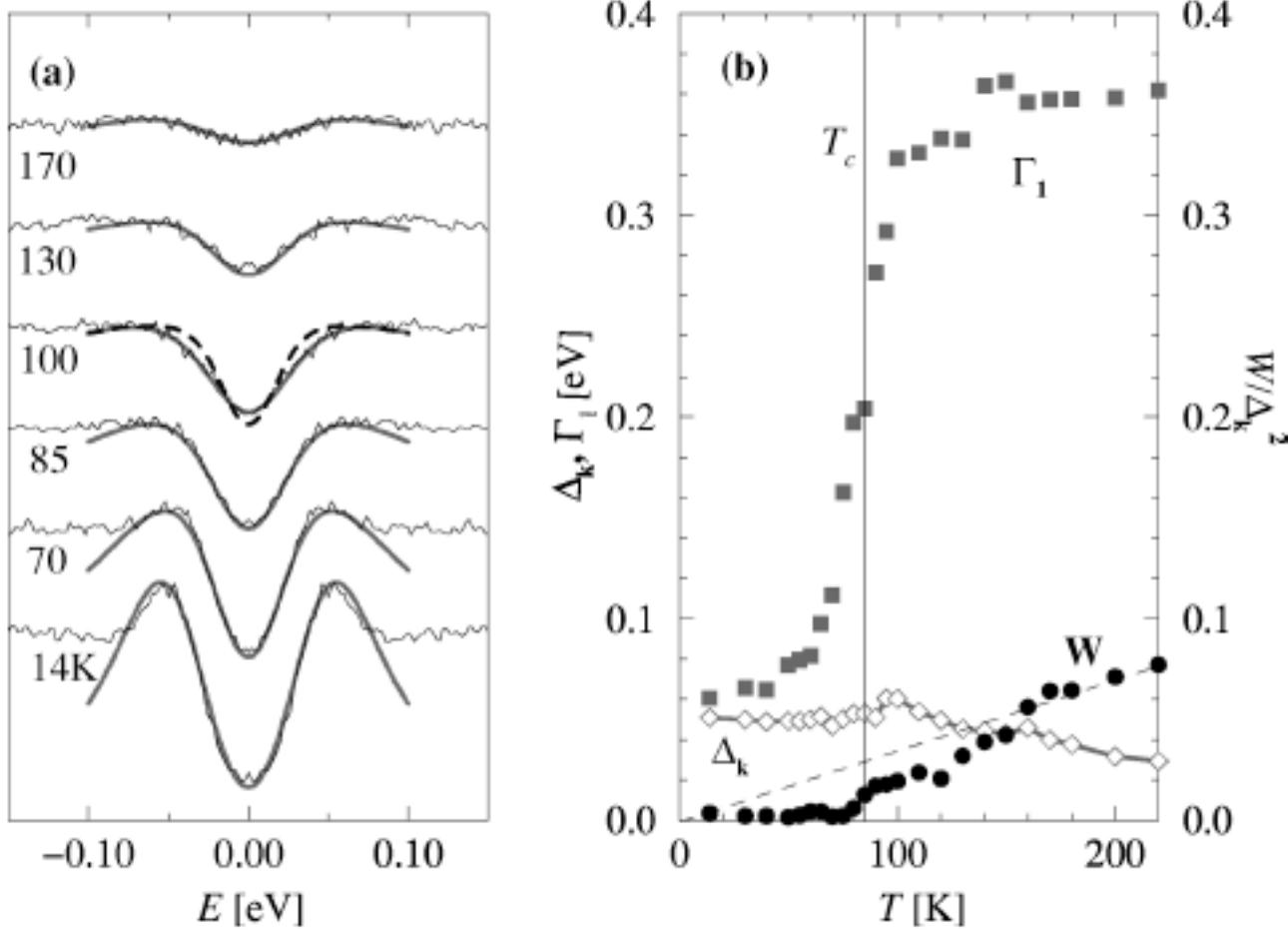


0 meV
and
36 meV
overlap



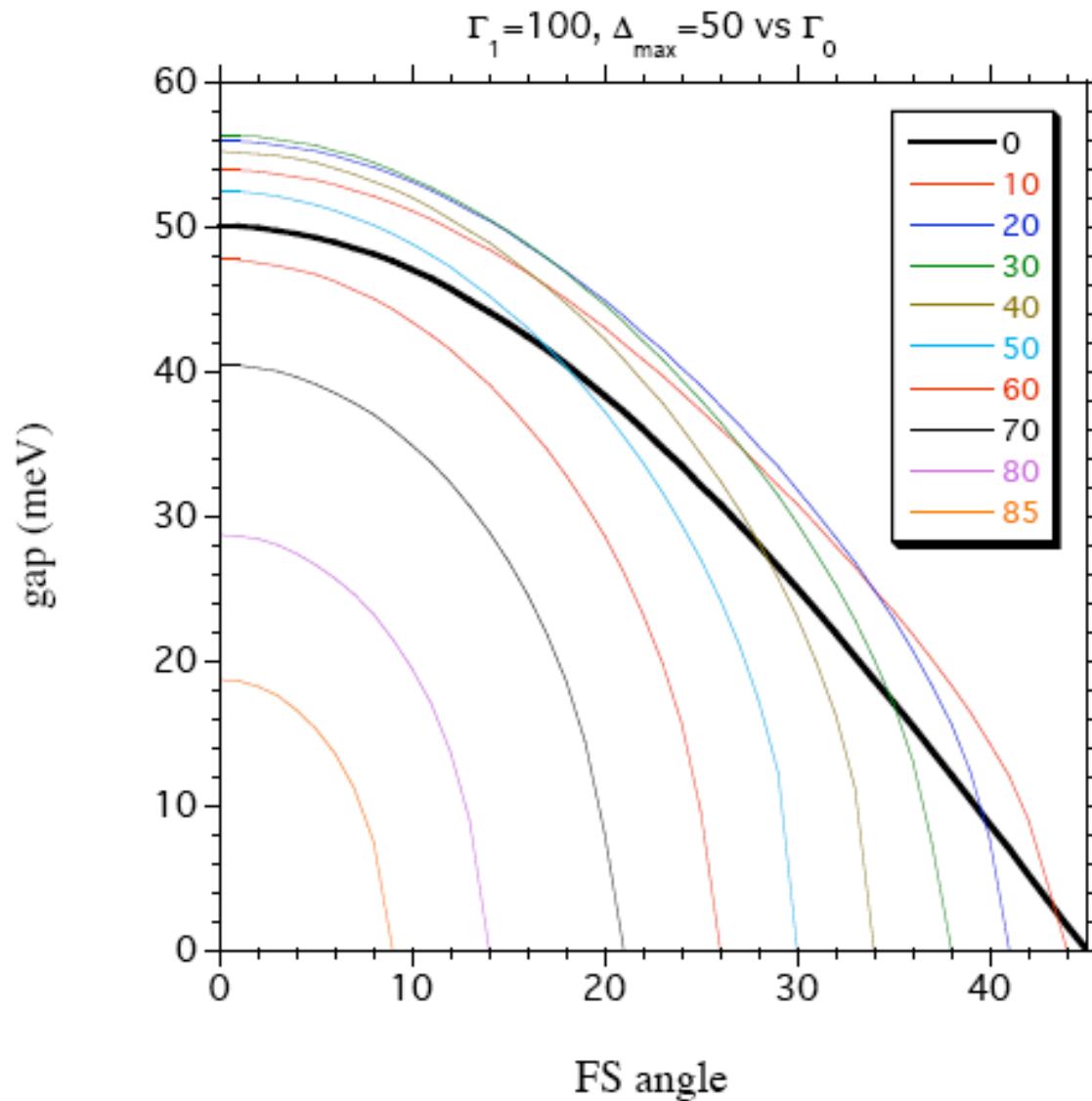
48 meV

Phase Fluctuations above T_c

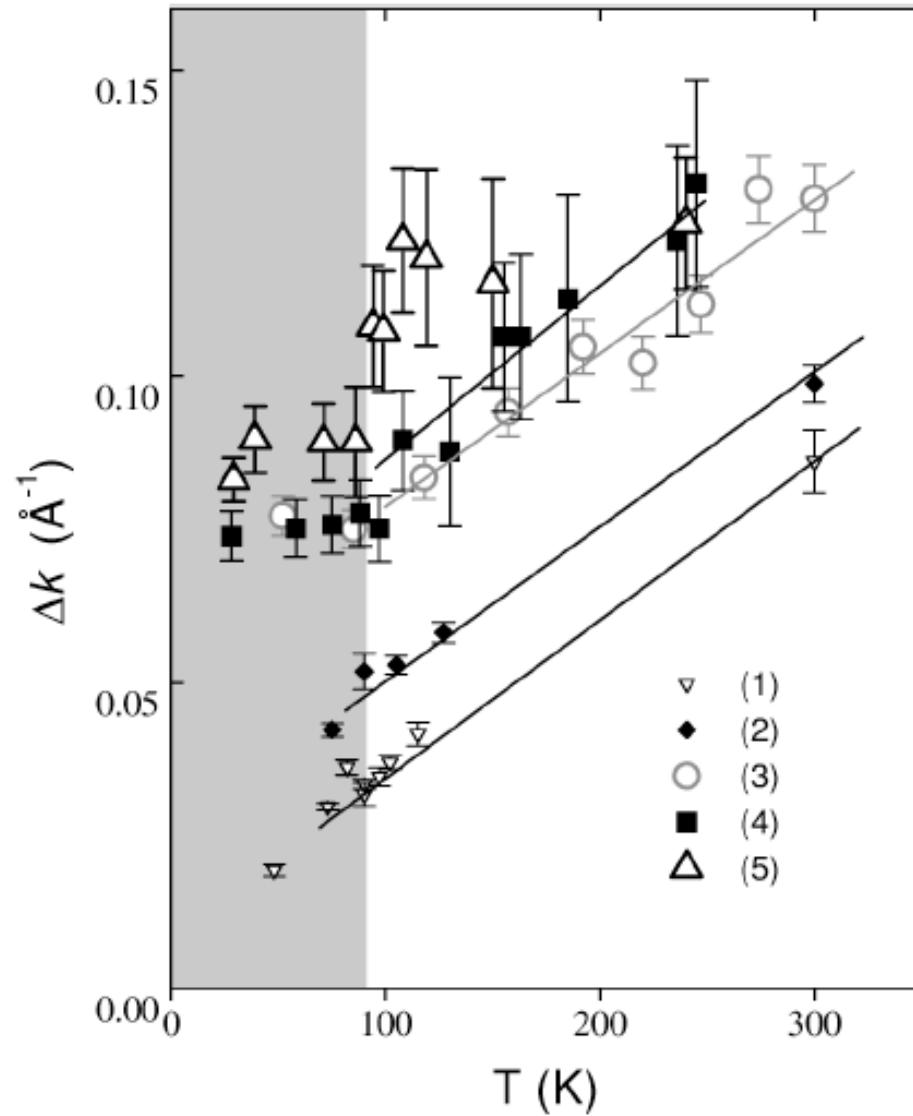


Franz and Millis, Phys Rev B 58, 14572 (1998)

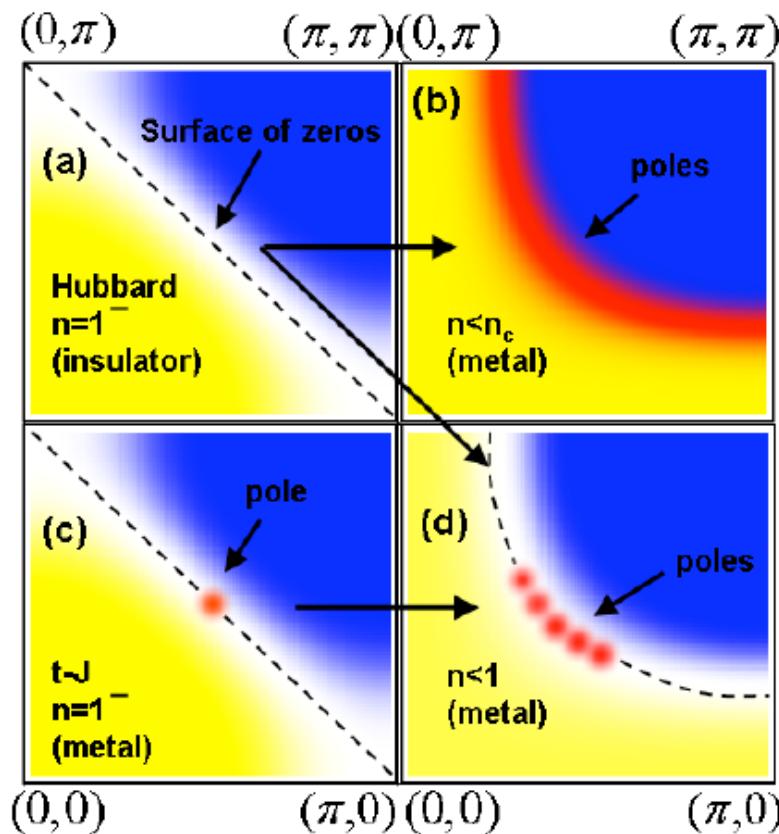
Arc Length is Linear in Γ_0 $\rightarrow \Gamma_0 \sim t \rightarrow$ Arc Length $\sim t$



Linear T scattering rate (Marginal Fermi Liquid)

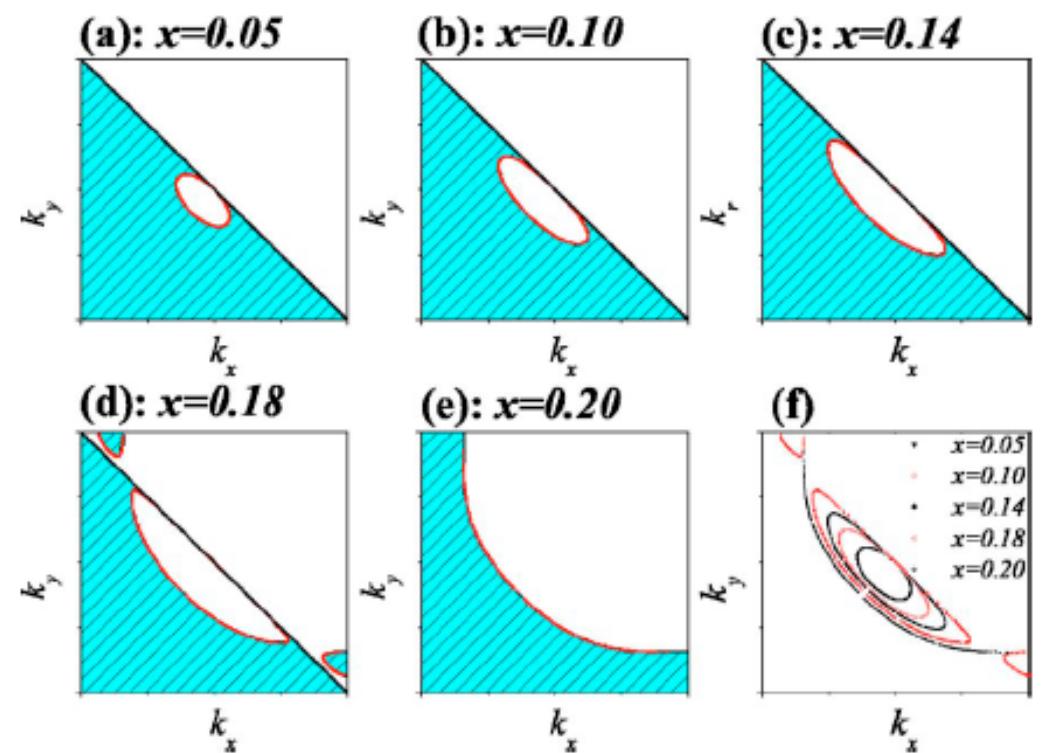


Valla *et al*, Phys Rev Lett 85, 828 (2000)



Stanescu, Phillips, Choy
cond-mat/0602280

Luttinger Zeros



Yang, Rice, Zhang
Phys Rev B 73, 174501 (2006)

SUMMARY

1. Spectroscopic data can be scaled as a function of $T/T^*(x)$
2. Fermi arc length is linear in T
3. Pseudogap appears to distort in shape as a function of T
4. No shadow bands are found associated with finite q vector
5. Pseudogap is tied to k_F and E_F implying a $q=0$ instability